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# Integration and Control of Wind Farms in the Danish Electricity System

Akarin Suwannarat

PhD Thesis

Institute of Energy Technology, Aalborg University, Denmark
November 2007

# Integration and Control of Wind Farms in the Danish Electricity System

**Akarin Suwannarat**

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**Institute of Energy Technology, Aalborg University**
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**November 2007**

# Integration and Control of Wind Farms in the Danish Electricity System

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**November 2007**

# Preface

This PhD thesis is intended to be used as the project description and the final report of the PSO-4102 project “Integration and Control of Wind Farms in the Danish Electricity System”. This project is made jointly between the Institute of Energy Technology; Aalborg University, DONG Energy, Risoe National Laboratory; Technical University of Denmark, Vattenfall, and the following group of Energinet.dk. This research project is funded by the 2004-PSO-programme. This project has been carried out from November 2004 to October 2007.

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Most of all, I would like to thank my family, especially my parents, who raised me and financially supported me until I finished my M.Sc., thus enabling me to devote myself to my PhD study. My parents and my brother have been a great source of moral support and encouragement during the preparation of this thesis. Finally, I would like to thank my girl friend, for encouraging me during times when the research was not running smoothly.

Akarin Suwannarat
Aalborg, 2007

# Contents

# Chapter 1

# Introduction

In this chapter, general information of the Danish power system is introduced. The wind power status and the challenges in power system operation with large amount wind power integration in Denmark are presented. The impacts of large scale wind power penetration in the Danish power system are described and the power balancing control issue is demonstrated. Research objective and approach including problem statement of the research project "Integration and Control of Wind Farms in the Danish Electricity System" is also described. The PhD thesis outline, which describes the research procedure of the development and implementation of model, control strategies and power system analysis, is also included.

## 1.1 Danish power system with wind power

Large interconnected power systems are among the most complex machines devised by man. As critical infrastructure for modern economies, the requirement of robustness and reliable operation are significant. Power system engineers must ensure that these requirements are met as the system evolves over time to meet new demands. This challenge and the complexity of the fundamental technical issues have driven the continuous development and improvement of analytical tools and techniques for analysing power systems. Theories and calculation techniques developed many decades ago have been refined and adapted for a range of computer programs that comprise the toolbox that power system engineers use to ensure that the interconnected power system reliably operates.

A large amount of wind power generation has been added to the Danish power systems as an energy source, therefore the generation needed to maintain system balance between generation and consumption is already present as part of the system. A small amount of additional regulation or load following capability is generally added that is most provided by existing power generating units. The rapid increase in large scale wind power generation in recent year has raised the visibility of an issue that has been challenging power grid planners and operators for years in how to deal with large amounts of intermittent generation resources connected to the grid.

### 1.1.1 Power generation and wind turbines

Denmark today probably has the highest wind power penetration level in the world [1]. The Danish maximum system generating capacity in 2003 was 13.31 GW. The peak load in west Denmark (Energinet.dk-west) in 2002 was 3.68 GW, the minimum load was approximately 1.2 GW. The peak load in eastern Denmark (Energinet.dk-east) was 2.68 GW and the minimum load was 0.83 MW. The net electricity generation was 43.8 TWh and the final consumption 32.4 TWh [2]. The Danish electricity supply is mainly based on coal and gas; however, wind power covers almost 25% of the total generation capacity [1]. Beside wind power, western Denmark also has a high amount of distributed generation by means of Decentralized Combined Heat and Power (DCHP) units. The Energinet.dk-west is the transmission system with the largest fraction of decentralized generation in Europe. Only 46% of the installed generation capacity consists of traditional large thermal plants [3]. The power production and power export curve for the year 2004, in Figure 1-1, shows how large a share of the demand is covered by productions from wind turbines and DCHP units: 50% of the time, wind and DCHP together cover 50% of the electricity demand [3]. Figure 1-2 depicts the growth of wind power during the last decade in Denmark. The development of the scale of individual wind turbines introduced on the market is depicted in Figure 1-3.

### 1.1.2 Wind power status and challenges

The total installed power and the numbers of turbines in Denmark has had a continually increase until 2002. During 2001 to 2003 a replacement agreement was carried out, where smaller and badly placed turbines were replaced with bigger turbines. 1,300 old turbines with a power of about 100 MW were replaced by 300 new turbines with a power of 300 MW [2].

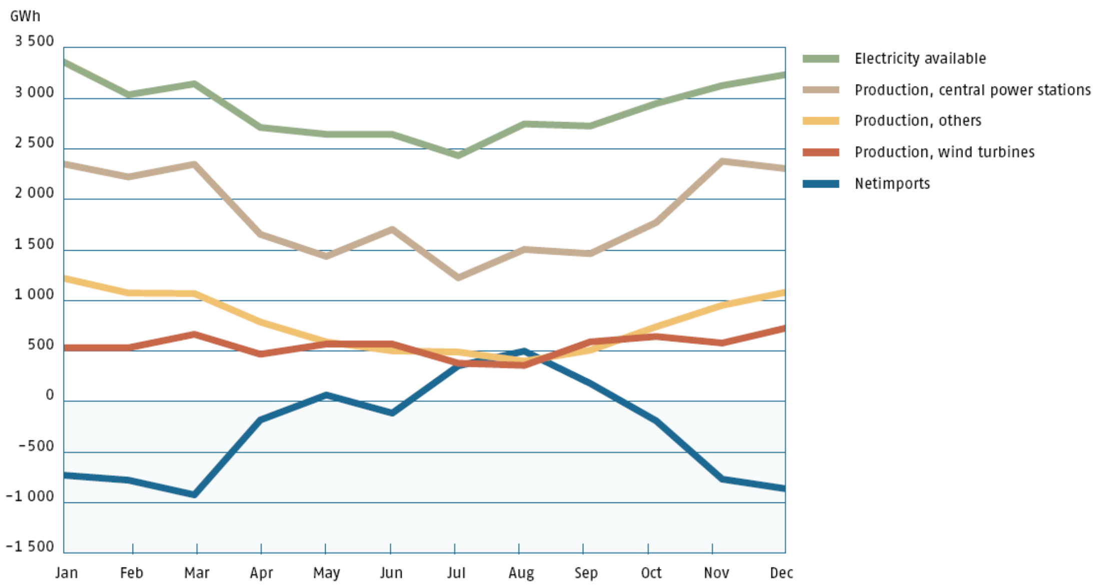


**Figure 1-1. Power production and power export in 2004 [3]**

In 2004 a new replacement agreement running to 2009 was introduced. The agreement involves replacing 175 MW old turbines with 350 MW new turbines. However, the agreement has until now had a limited effect. Offshore wind power is becoming significant in Denmark: 427 MW are presently in operation, including the large offshore wind farms of Horns Rev A (HRA) in the North Sea and Rødsand A (ROA) in the Baltic Sea. The commissioning of Horns Rev B (HRB) and Rødsand B (ROB) wind farms are planned to become operational in 2009-2010 [2], [8]. At the end of 2004 the installed wind power in Denmark was 3117 MW. This is 23.4% of the net generation capacity in the country [4]. Denmark already satisfies 21% of its national electricity needs from wind power, and the target is to increase this to 25% by 2010. Grid integration of up to 50% (6 GW) wind energy in the Danish electricity system by 2025 is technically and economically feasible according to a recent study from the former system operator Elkraft System (Energinet.dk-east). In Figure 1-4, the present and projected offshore wind farms in Denmark are depicted.

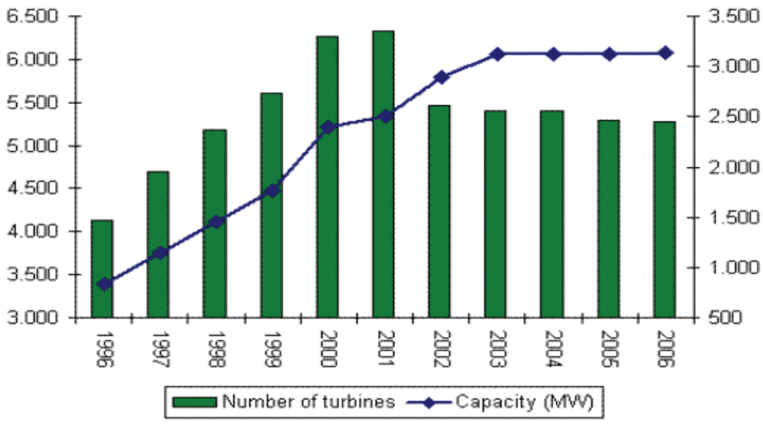


**Figure 1-2. Installed wind power in Denmark [5]**

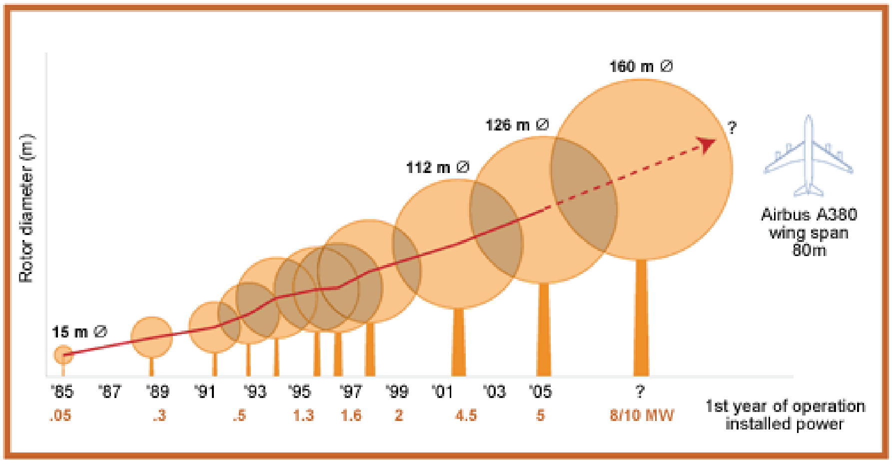


**Figure 1-3. Wind turbine development [6]**

Integration of wind farms into the power system presents challenges to power system planners and operators. These challenges stem primarily from the natural characteristics of wind farms which differ in some respects from conventional power plants. Wind farms are not dispatchable in the traditional sense, which lessens the ability of system operator to control them. This leads to a concern among operators unfamiliar with wind power about wind power impacts on the real time process of maintaining the system balance between generation and consumption. The key integration question then become how the variation in wind farm power production affect the operation of the power system on day to day basis with regard to system reliability, effect on load variability, variation of impacts with wind power penetration, and requirement of reserve from dispatchable generation. At the power system level, the aggregate performance of a large number of wind turbines is generally more important than the details of an individual wind turbine.

Wind turbines are usually spread out over a significant geographical area within the wind farm, and multiple wind farms are distributed over a much larger area within the balancing area. This spatial diversity has the beneficial effect of smoothing some variations in electrical power production. Wind power generation is driven by the same physical phenomena that control the weather as the uncertainty associated with a prediction of future generation is more significant. The combination of production variability and higher uncertainty of prediction can make it more difficult to fit wind power generation into established procedures for power system operations, planning, and scheduling.


**Figure 1-4. Present and projected locations of offshore wind farms in Denmark [7]**

## 1.2 Impacts on power system operation

As more wind power generation is connected to utility systems, it becomes important to understand and manage the impact of wind generation on system operations. Recent studies and simulations provide a better understanding of these impacts, and with this knowledge, progress is now being made in developing the tools and methods to minimize costs and operate reliably with higher levels of wind generation. The analyses from which the conclusions regarding impacts are drawn typically consist of primary elements, such as centralized thermal power plants and DCHP units. Steady-state analysis utilizes appropriate base-cases that are developed. Stability analysis assesses the effects of the new facility on the ability of the power system to recover from major disturbances without cascading outage of additional equipment.

The already established control methods and backup available for dealing with variable demand and supply are more than adequate for dealing with the additional variable supply such as wind power at penetration levels up to around 20% of gross demand, depending on the nature of a specific system. For larger wind power penetration levels, some changes may be needed in power systems and their methods of operation to accommodate the further integration of wind power generation. In Denmark, the country with the highest penetration of wind power in the world, 17% of total consumption was met with wind power in 2004. In the western Danish transmission system, which is not connected to the eastern part of the country, 25% of electricity demand is met by wind power in a normal wind year and the wind has been able to cover 100% of instantaneous demand on some occasions. The integration of large amounts of wind power is often dismissed as impossible and many grid operators are reluctant to make changes in long established procedures to accommodate wind power. In Denmark, the Transmission System Operator (TSO) was initially sceptical about how much wind power the system could cope with [8].

System integration of large scale wind power is raising a long list of important issues that must be evaluated. This includes transmission capacity, frequency control, voltage stability, power balance control and reserves. Frequency control problems can be found in power systems, such as a stand alone system and small systems with large scale wind power penetration. On the large interconnected systems, power balance problem is one of the main challenges. Therefore, the major issue in this research project is to comply with the fluctuating nature of wind power production. The power fluctuations generated by wind farms at different weather conditions are of interest with respect to the needed regulating power. The power fluctuation generated from the offshore wind farms may give a significant contribution to the deviation from the planned power exchange between the western Denmark and Germany, the UCTE (Union for the Coordination of Transmission of Electricity) system. These unscheduled power flows could reduce system stability and increasingly affect trading capacities.

### 1.2.1 System balancing with wind power

The impacts from wind power variation on system stability are captured by different time frames. Frequency regulation, handled by AGC (Automatic Generation Control) and governor action, takes place in the time frame of a few seconds to about a minute. Load following, handled by economic dispatch and operator action to deal with variations from load and generation forecasts and guided by the unit commitment schedule for that day, takes place in the time frame of a few minutes to a couple of hours. For wind power generation, the questions are: How do the variability and forecasting accuracy affect the deployment and operation of other generating resources in a balancing area. The presence of significant amounts of wind generation in a balancing area may often require some prudent adjustments to operating strategy. The objective today has turned to identifying methods for quantifying the economic impacts of these changes, assessing the technical impacts of wind generation on system performance and reliability, and engineering solutions to minimize these impacts.

Large-scale integration of wind power into power system operation gives rise to new challenges for the entire system and for transmission system operators in particular. With regard to their system responsibility, the supply of reliable electric power includes the responsibility to maintain a balance between production and consumption in the power system. Large scale wind power penetration levels; however, requires a rethinking of the power system operation methods because wind power cannot be scheduled with the same certainty as conventional power plants.

Large scale wind turbine installations represent a new challenge to the Danish power system operation. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control and balancing problems. The rapid power fluctuations from wind farm will also contribute to the planned power exchange deviation between the western Denmark and Germany. Power balancing control should be developed to manage the imbalance taking into account the uncertain nature of wind power. Wind power represents a variable generation source due to changing wind conditions. The impact of wind power depends mostly on the wind power penetration level, but also depends on the power system size, generation capacity mix, the degree of interconnection to neighbouring systems and load variations.

The important wind power fluctuations for the operation of a power system are mainly caused by daily weather patterns. The wind power fluctuations caused by turbulences or gusts, however, have almost no impact so far on power system operation [2]. Due to the geographical distribution of the onshore wind turbines, the power fluctuations are much smaller as compared to the variations at the offshore wind farm. However, with an increasing number of large offshore wind farms in the future, short-term fluctuation may become an issue. The offshore wind farm Horns Rev with 80 wind turbines totalling 160 MW in an area of 20 km$^2$, has experienced power output fluctuations of up to 100 MW in 10-15 min. [2], [8].

From a system point of view, large power variations become a problem if they are not predicted accurately in the forecasting system. For instance, wind power reductions due to the cut-off wind speed can, in extreme situations, lead to very large power deviations. The rather limited wind power variations in the short term can be well handled by the capabilities of the existing systems.

The western Danish power system is subjected to transits between two synchronous areas operated on different conditions. The power exchange with the Nordel system is arranged through the High Voltage Direct Current (HVDC) connections and controlled each 15 minutes. On the other hand, the planned power exchange with the UCTE system is controlled each 5 minutes [2]. This introduces a challenge with regard to keeping the power balance in the Danish power system and complying with planned power exchange with the Nordel and the UCTE systems. This project focuses on solving the power imbalance caused by rapid fluctuations observed in the offshore wind farms and also to examine the ability of the secondary control of the power generating units to reduce the affect caused by wind power fluctuations in the Danish power system.

### 1.2.2 Power balancing control

Large amounts of wind power generations may challenge the reliability of the electricity system as wind productions change rapidly and unexpectedly due to wind speed fluctuations. Wind power generations also challenge the power system adequacy due to the imbalance of wind power generations and consumptions. The reliability is ensured by power generating units in operation and by power system components. The rapid change in wind power productions may challenge reliability. The fluctuating production from wind power sources may cause a problem to system adequacy, if the power production capacity is not sufficient to meet the demand at all times. Wind power is not the only cause of imbalance in power system operation. Other reasons for deviations between the planned power and actual operation are error in consumption forecasts, operating problems at power plants and transmission system. The final matching of power generation and consumption is so called power balancing, which is handled by the TSO.

Variability and controllability of wind power will affect the need for the secondary reserve. If thermal power production is replaced by wind power, this will have an effect on the system reliability. Its effect on the production of the wind farm has to be considered. Power system reliability can be affected by extreme wind conditions since they may result in loss of a large amount of wind power within minutes. The fluctuating nature of wind power introduces several challenges to reliable power system operation and contributes to deviations in the planned power generation which can lead to power system control and balancing problems. System reserve availability and ramp rates capability of generation units are taken into consideration when analyzing the power balance control.

# 1.3 Research objective and approach

The Danish power system starts to face problems when integrating thousands megawatts of wind power, which produce in a stochastic behaviour due to natural wind fluctuations. With wind power capacities increasing, the Danish TSO is faced with new challenges related to the uncertain nature of wind power. The fluctuating nature of wind power introduces several challenges to reliable power system operation and contributes to deviations in the planned power generation which can lead to power system control and balancing problems. In order to analyze the effects resulting from the structural changes in power generation and system operation by the penetration of large scale wind farms, the project "Integration and Control of Wind Farm in the Danish Electricity System" is set up. This project is made jointly between the Institute of Energy Technology; Aalborg University, DONG Energy A/S, RISØ national laboratory, Vattenfall A/S, and Energinet.dk A/S, and funded by the 2004 – PSO – programme.

## 1.3.1 Problem statement

The random nature of the wind energy supply means that control and compensation of regulating power requirement, for the provision of which TSOs are responsible, are constantly increasing. In an offshore wind farm, the power fluctuations can be much more intense than from the aggregated wind power production on land, due to the geographically distributed nature of wind production. The active power fluctuation have been measured and found to be in the time scale from minutes to a few hours [3]. Wind power is characterized by fluctuations of the produced active power due to the wind fluctuating nature. With the increase of large scale offshore wind farms in the future, the fluctuating nature of wind power may introduce several challenges to reliable operation of power system and would lead to power system control and balancing problems.

The Danish electricity system consists of two separate synchronous areas: energinet.dk-east which is synchronized to the Scandinavian Nordel system and energinet.dk-west which is synchronized to the UCTE system. The transmission systems are presently separated into two synchronous areas that are not connected to each other. A significant proportion of the generation comes from wind turbines and DCHP units. The total installed wind power is approaching 23% of the yearly power consumption [8]. The western Danish power system contain 400 kV and 150 kV transmission system with the HVDC connections to Nordel systems (Norway and Sweden) in the north and the 400 kV AC connection to the UCTE system (Germany) in the south. At 20 % wind power capacity, the western part of Denmark with the highest concentration of wind turbines now experiences short periods where wind energy delivers 100 % of the electricity consumption [8]. Denmark has to export the surplus amount of electricity to Germany, Sweden and Norway. At 50 % wind power penetration, this situation will be much more frequent. With 75% of the Danish wind power capacity installed in the western part of Denmark; this is where the power system impacts are.

### 1.3.2 Research objective

Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generating units. These include centralized thermal power plants, as well as the fast secondary control from the DCHP units, to smooth out fluctuating power from wind turbines and increase the overall reliability of the power system.

The main target here is to keep the power generation in balance to the power consumption and to keep the power exchange between the western Danish power system and the UCTE system (Germany) at the planned power exchange. Earlier studies in [2] have shown that the power exchange through the HVDC links with the Nordel system is limited with the new settlement model. Therefore, the better and more intense use of domestic regulating power is required.

In this project, the generic models of an AGC system, wind farm, conventional power plant and DCHP unit for long-term dynamic simulation should be implemented and developed. A generic model with a similarity to the Danish power grid including the system interconnections with neighbouring countries should be set up and the active power balance should be taken into account. An aggregated wind farm model with wind farm power control system should be developed. The DCHP plant model should be implemented and it is analysed whether the power control should be changed with regard to taking part in the reserve. In the centralized thermal power plant model, secondary control and thermal dynamics of the boilers must be included.

The total generic model will be used to evaluate the active power balance, power system stability at different control strategies in the wind farms and at different loads and production conditions. Control strategies for the wind turbines in the wind farms with regard to power balancing control and the system stability should be analyzed. The operation and control of the power system for the different control strategies should be analysed both at normal conditions and during very fluctuating power production from the wind farms. The power system analysis will focus on the power control from wind turbines in relation to the secondary control on the power plants and the interconnections with neighbouring countries.

### 1.3.3 Research approach

The topic being interested in this research project is the impact of large scale wind power integration on power balancing control in the Danish power system. The frequency stability is not of interest in this project as the Danish power system is interconnected with the UCTE system. The shortest time constants in electrical power system are in millisecond, while the measured generation and load time series of 30 seconds up to 15 minutes are used in the project. In order to observe the phenomena of interest, a relative long-term simulation is necessary. An appropriate simulation approach has been developed which is often referred to as power system dynamic simulation. In this research project, the power system simulation software DIgSILENT Power Factory is used.

The first step to be taken in order to be able to use this program for the investigation of the impacts of large scale wind power integration in the power system is therefore to implement and develop the generic models of power generating units for long-term dynamic simulation. The dynamic simulation studies based on the implemented and developed models of an AGC system for long term dynamic simulation, an aggregated model of a centralized thermal power plant for designing AGC system, an aggregated wind farm model with wind farm power control system, an aggregated model of DCHP plants including the power control and the system interconnections with the UCTE and the Nordel systems are demonstrated. The utilization of the regulating power control of the Great Belt Link HVDC connection between the eastern and the western parts of Denmark is analyzed. Simulation results of the developed models are presented, compared and validated with the simulations of the detailed models and the measurements.

The next step is to investigate the impact of wind power on Danish power system behaviour. Sensitivity analyses for dynamic simulation of impacts of large scale wind power penetration on the Danish power systems with regard to long-term stability are presented. Evaluation of the simulation results from the sensitivity analysis, which can be used to illustrate a possible control concept to achieve active power balance with the increased wind power penetration, are expected. Finally the operation and control of the Danish power system with large scale wind power penetration is analyzed.

## 1.4 Thesis outline

The structure of the PhD thesis reflects the research approach discussed above. This thesis is presented in the following chapters. In chapter 2 an overview of the Danish electricity system is given. The various power generating units including centralized thermal power plants, decentralized combined heat and power units, on-land wind turbines and wind farms in the Danish power system are presented. This chapter also contains an overview of the Great Belt Link HVDC connection and the system interconnections with Nordel system and UCTE system.

In chapter 3, an overview concept of development and implementation of models is presented and the modelling approach is discussed. An aggregated model of the Danish power system for long-term dynamic simulation is presented. The general working principle of AGC system is introduced and the AGC model with wind power integration is developed. The modelling approach will also be applied to each of the system components as will be described in chapter 4 and chapter 5. Simulation studies of the AGC system with wind power integration for dynamic power system simulation in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources is presented.

In chapters 4 and 5, models of power generating units and system interconnections are implemented and developed. In chapters 4, an aggregated model of centralized thermal power plant with the secondary control and thermal dynamics of the boilers is implemented. The DCHP plant model is implemented and it is analysed whether the power control should be changed with regard to taking part in the secondary control. An on-land wind turbine model and an aggregated wind farm model which include wind farm power control system for long-term dynamic simulation are also implemented and developed here. In chapters 5, an overview of the interconnections with the UCTE system and the Nordel system are presented. Simplified models of the interconnections with the UCTE system and the Nordel system are developed. A general background of the Great Belt Link (GBL) HVDC connection between the eastern part and the western part of the Danish power system is presented. A simplified model of GBL HVDC connection with regulating power control system is implemented. A preliminary validation of the models is carried out and the simulation results associated with model validation are commented. The capability of each of the power generating units is analyzed in this chapter.

In chapter 6, control strategies for the domestic power generating units for long-term dynamic simulation is presented and described. The derived models from chapters 4 and 5 are used to draw conclusion with respect to different power balancing control strategies. Simulation studies of the utilization of the domestic regulating power control from centralized thermal power plants, DCHP units and wind farms are carried out. Simulation studies of the utilization of the regulating power control from the GBL HVDC connection are presented and discussed.

In chapters 7 and 8, the derived models are used to draw conclusion in several simulation case scenarios with regard to power balancing control issue. In chapter 7, dynamic sensitivity analysis with the needs to determine which input parameters contribute the most to output variability for different case scenarios is introduced. Dynamic sensitivity analysis for the domestic power generating units is presented and discussed. The dynamic sensitivity analysis of power system operation with different share among centralized power plants and decentralized generating units are also carried out in this chapter. In chapter 8, several simulation scenarios with large scale wind power penetration for long term dynamic simulation is carried out. System analysis with present status of wind power penetration in Denmark is presented. Commissioning of the HRB wind farm is discussed. Simulation studies of the increased large scale wind power penetration in the Danish power system are carried out.

In chapter 9, the conclusions of the derived models and developed control strategies are summarized and the conclusions of scenarios simulation studies from the research project are also given.

# Chapter 2

# Danish Power System Operation

## 2.1 Introduction

This chapter gives an introduction to the Danish power system and power generation with wind turbine in Denmark. First, an overview structure of the Danish power system is given. The general structure of the eastern part and the western part of the Danish power system is described.

The main part of this chapter is devoted to power generating units. The various types of power generating units in the Danish power system including conventional centralized thermal power plants, decentralized combined heat and power units, on-land wind turbines and offshore wind farms are presented and described. Then, an overview of the system interconnections with Nordel and UCTE systems and the Great Belt Link HVDC connection between the eastern part and the western part of Denmark are also described.

Finally, the challenge in Danish power system operation is discussed. An example of the situation when a storm affected the southern Scandinavia on 8 January 2005 is given. The impact of the situation on power system operation is discussed. It is also pointed out that due to the increasing of wind power generation in Denmark, power fluctuation generated from wind turbines may cause much more challenges in power balancing control to the power system operation.

## 2.2 Danish power system

Denmark is situated between the Nordel system a hydro power dominated system and the UCTE system a fossil dominated system. The Danish electricity system, as shown in Figure 2-1, consists of two separate synchronous areas: energinet.dk-east which is synchronized to the Scandinavian Nordel system and energinet.dk-west which is synchronized to the UCTE system. The transmission systems are presently separated into two synchronous areas that are not connected to each other. The Danish power system is characterized by significant incorporation of dispersed generation and wind power.

The power supply from the centralised power plants is reduced on favour of dispersed generation and wind power. Presently, more than 23% of the annual electricity consumption is corresponded by the electricity production from wind turbines [8]. Denmark today probably has the highest wind power penetration level in the world [1]. The largest increase in grid-incorporated wind power is expected to come from large offshore wind farms operating as large wind power plants, connected to the transmission system and providing ancillary services to the system [9]. The structure of the Danish power system is illustrated as shown in Figure 2-2. With 75% of the Danish wind power capacity installed in the western part of Denmark; this is where the impacts on power system operation are.

The general structure of the eastern part and the western part of Danish power system is described as follow:

**a) The eastern Danish power system**

The area of the TSO of the eastern Denmark, Energinet.dk-east includes the island of Zealand and a number of small islands. The transmission system is operated at 400 kV and 132 kV. In the north, the eastern Danish power system is connected to Sweden, the Nordel area, via 400 kV and 132 kV AC cables. In the south, the eastern Danish power system is connected to Germany, the UCTE area, via HVDC links.

The installed wind power corresponded to about 14% of the generation capacity of the area, whereas wind power covered about 12% of the electrical energy consumption of the eastern Denmark. A new large scale offshore wind farm ROB with rated power of 215 MW is planned to be set in operation in 2009-2010 [8].

**b) The western Danish power system**

The area of the TSO of the western Denmark, Energinet.dk-west includes the peninsula of Jutland, the island of Funen and a number of small islands. The transmission system is operated at 400 kV and 150 kV. In the north, the western Danish power system is connected to Norway and Sweden, the Nordel area, via 5 HVDC links. In the south, the western Danish power system is connected to Germany, the UCTE area, via 400 kV and 220 kV AC-lines.

In western Denmark, the primary power plants are thermal, coal- or gas-fired units. A significant proportion of the power generation comes from on-land wind turbines and DCHP units. In the year 2004 the installed wind power corresponded to about 33% of the generation capacity of the area, whereas wind power covered about 23% of the electrical energy consumption of the western Denmark. A new large scale offshore wind farm HRB, with rated power 215 MW, is planned to be set in operation in 2009-2010 [8].

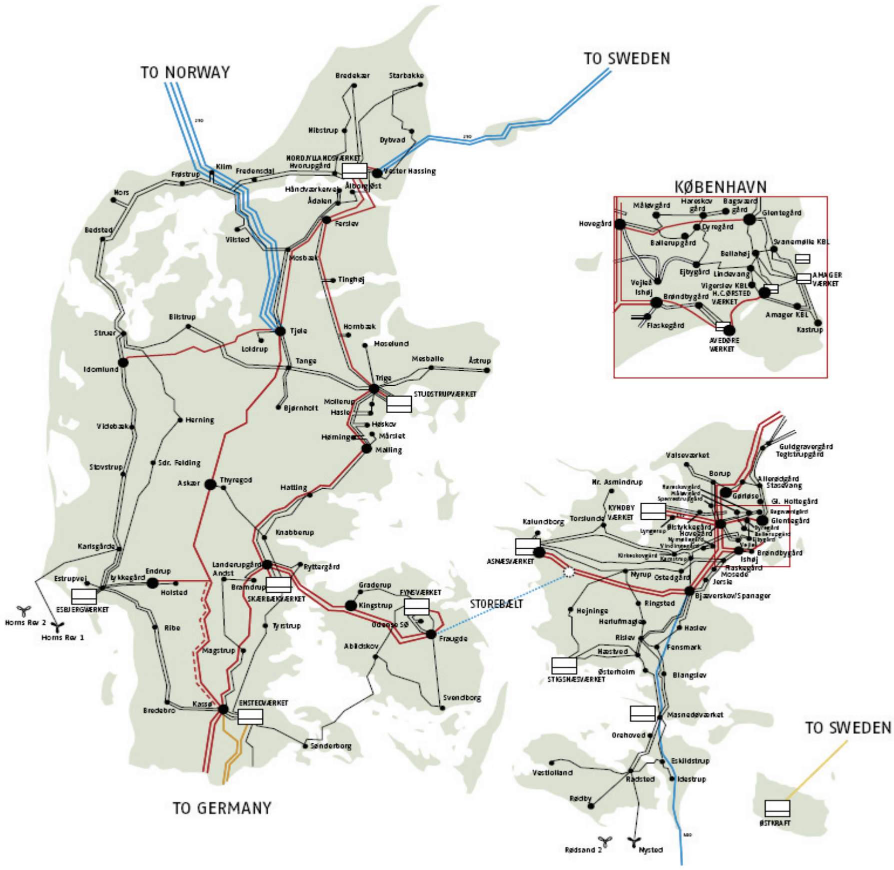


**Figure 2-1. The Danish power system [3]**

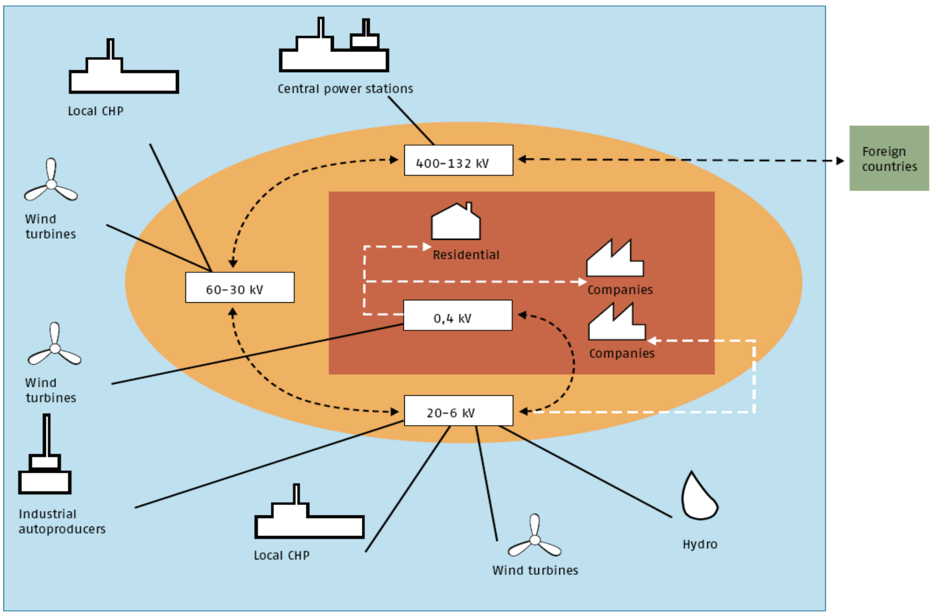


**Figure 2-2. Structure of the Danish power system [3]**

## 2.3 Conventional power generations

The Danish power system consists of different technologies in power generating units, such as centralized conventional power plants with steam turbines, decentralized combined heat and power units with gas turbines. Figure 2-3 depicts a diagram of the total electrical energy generation by raw energy in Denmark for the year 2004. The Danish electricity generation has changed from being entirely based on fossil fuel to a much more environmentally friendly mix of renewable energy. Presently, 17% of the annual electricity consumption in the Denmark is corresponded by the electricity production from wind turbines [3]. The power generating units in the Danish power system, except wind power generation, in the western and the eastern Denmark can be described by the different technology concepts as shown in Table 2-1 and Table 2-2 respectively.

**TABLE 2-1**
**POWER GENERATING UNITS IN THE WESTERN DANISH POWER SYSTEM [10]**

| Power Generation types | No. of units | Installed MW | Voltage system |
|---|---|---|---|
| Others | 2 | 0.12 | < 50 kV |
| Photovoltaic | 1 | 0.10 | < 50 kV |
| Hydro | 51 | 10.68 | < 50 kV |
| Gas Turbine | 34 | 147.37 | < 50 kV |
| **Gas Turbine** | **4** | **60.80** | **≥ 50 kV** |
| Combined Cycle | 2 | 14.50 | < 50 kV |
| **Combined Cycle** | **7** | **314.60** | **≥ 50 kV** |
| Bio Internal Combustion Engine | 148 | 62.36 | < 50 kV |
| Gas Internal Combustion Engine | 476 | 731.34 | < 50 kV |
| **Gas Internal Combustion Engine** | **1** | **30.00** | **≥ 50 kV** |
| Steam Turbine with steam condensation | 1 | 8.60 | < 50 kV |
| **Steam Turbine with steam condensation** | **2** | **432.00** | **≥ 50 kV** |
| Steam Turbine with back pressure operation | 18 | 104.60 | < 50 kV |
| **Steam Turbine with back pressure operation** | **17** | **3,330.10** | **≥ 50 kV** |
| Diesel Motor Internal Combustion Engine | 4 | 0.30 | < 50 kV |

**TABLE 2-2**
**POWER GENERATING UNITS IN THE EASTERN DANISH POWER SYSTEM [10]**

| Power Generation types | No. of units | Installed MW | Voltage system |
|---|---|---|---|
| **Avedøreværket (block2) power plant** | **1** | **560.00** | **≥ 50 kV** |
| Photovoltaic | 3 | 0.08 | < 50 kV |
| Hydro | 2 | 0.03 | < 50 kV |
| Gas Turbine | 8 | 6.67 | < 50 kV |
| **Gas Turbine** | **8** | **381.30** | **≥ 50 kV** |
| Combined Cycle | 1 | 13.30 | < 50 kV |
| **Combined Cycle** | **2** | **90.00** | **≥ 50 kV** |
| Gas Internal Combustion Engine | 218 | 248.93 | < 50 kV |
| **Steam Turbine with steam condensation** | **12** | **2,928.00** | **≥ 50 kV** |
| Steam Turbine with back pressure operation | 14 | 147.05 | < 50 kV |
| **Steam Turbine with back pressure operation** | **9** | **570.00** | **≥ 50 kV** |
| Diesel Motor Internal Combustion Engine | 2 | 30.00 | < 50 kV |

From Table 2-1 and Table 2-2, it can be seen that most of the centralized power plants are based on steam turbine technology (marked with green colour) and most of the decentralized power plants are based on gas turbine technology (marked with red colour). Therefore, an aggregated model of a centralized thermal power plant with steam turbine technology and an aggregated model of a DCHP unit with gas turbine technology should be implemented and developed as will be described in chapter 4.

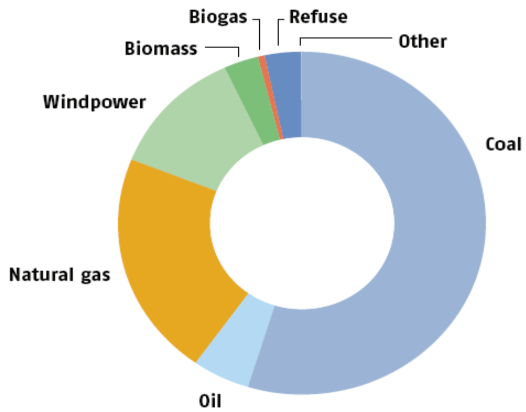


**Figure 2-3. The Diagram of total generation of electrical energy by raw energy [3]**

## 2.3.1 Centralized thermal power plants

There are six large thermal power plants in the east Denmark and other six large thermal power plants in the west Danish power system as shown in Table 2-3 and Table 2-4 respectively. The primary fuels used at these power plants are coal and natural gas. According to the power plant specifications [10], in Table 2-3 and Table 2-4, most of the large thermal power plants in Denmark are coal-fired Combined Heat and Power (CHP) units that can extract steam for heat production and have an operating domain between 20% and full power load without heat production.

## 2.3.2 Decentralized combined heat and power plants

A large amount of dispersed combined heat and power generations are installed in the Danish electricity system as shown in Figure 2-4. It can be seen that most of the decentralized power plants are based on gas turbine technology. These units are equipped with heat storage tank, so they can operate more independently from the heat demand [2]. The small DCHP units below 10 MW operate normally on-off depending on the tariffs. From January 2005, the DCHP units, with above 10 MW rated power, are involved to participate in the regulating power market and contribute to the power balance in the system. The utilization of the domestic regulating power resource as DCHP unit is among the vital arrangement for better power balance control. In this study, DCHP units with above 10 MW rated power are integrated within the AGC system, therefore spinning reserve can be ordered upon request.

**TABLE 2-3**
**CENTRALIZED THERMAL POWER PLANTS IN EASTERN DENMARK [11]**

| Power Plants | Active Power (MW) | Fuel |
|---|---|---|
| Amager | 477 | Coal |
| Asnaes | 1057 | Coal |
| Avedoere | 810 | Coal |
| H.C. Oersted | 273 | Natural Gas, Oil |
| Kundby | 734 | Natural Gas, Oil |
| Stigsnaes | 408.5 | Coal |

**TABLE 2-4**
**CENTRALIZED THERMAL POWER PLANTS IN WESTERN DENMARK [10]**

| Power Plants | Active Power (MW) | Fuel |
|---|---|---|
| Fynsværket B3/B7 | 246/360 | Coal |
| Studstrup B3/B4 | 350/350 | Coal |
| Nordjyllands B2/B3 | 285/380 | Coal |
| Skærbærværket B3 | 392 | Gas |
| Enstedværket B3 | 625 | Coal |
| Esbjergværket B3 | 378 | Coal |


**Figure 2-4. Centralized power plants (green square points) and decentralized CHP generations (red round points) in Denmark [3]**

## 2.4 Wind power generation

The installed power capacity of wind power approached 3,120 MW in the Danish power system (January 2005). In the eastern Danish power system area, Energinet.dk-east, the installed power capacity of wind turbines is around 740 MW. The installed power capacity of wind turbines in the western Danish power system area, Energinet.dk-west, is around 2,380 MW [4]. The amount of wind energy in Denmark includes three large offshore wind farms, an offshore wind farm HRA with 160 MW rated power in the western Denmark, and an offshore wind farm ROA with 165.6 MW rated power, and an offshore wind farm Middelgrunden with 40 MW rated power in the eastern Denmark.

In eastern Denmark, some increase in the wind power incorporated in on-land sites may come from the upgrading existing, small wind turbines to newer and larger ones, and also from the use of new sites on the islands of Lolland and Falster characterized by good wind conditions. The main increase in the wind power to be commissioned in the eastern Denmark will come from the construction of new, large offshore wind farms. Commissioning of the new offshore wind farm ROB, with a rated power of 215 MW, has been announced by the Danish Energy Authority, with completion expected by the years 2009–2010 [8].

In western Denmark, an increase in the wind power incorporated in on-land sites may occur by upgrading, replacement of existing (small) wind turbines with ratings below 1MW (up to 900 units with total 175MW) by new, more efficient wind turbines with ratings of several MW (between 150 and 200 units). This upgrading may give up to 350MW more local wind power in the whole country. However, the major upgrading is expected in Jutland, the continental part of the western Denmark. The increase in the wind power to be commissioned in the western Denmark will also come from large offshore wind farms. Commissioning of the new offshore wind farm HRB, with a rated power of 215 MW, will take place by the year 2009 [8].

Most of the wind turbines and wind farms which are installed in the Danish electricity system are mainly two different wind turbine technologies.

a) Fixed speed, active-stall, wind turbines equipped with squirrel-cage induction generators (SCIG)
b) Variable speed, pitched control, wind turbines equipped with doubly-fed induction generators (DFIG)

In this project, the wind power generation units in the Danish power system are separated into 2 categories, on-land wind turbines and large scale offshore wind farms.

### 2.4.1 On-land wind turbines

On-land wind turbines are installed throughout the country as shown in Figure 2-5. The majority of on-land wind turbines in the Danish power system are fixed speed, active-stall, wind turbine equipped with squirrel-cage induction generator; the detailed data of all wind turbines in the Danish power system is described in [13]. A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output. Power systems have flexible mechanisms to follow the varying load and plant outages that cannot always be accurately predicted. The small correlation between the total output powers of the different wind turbines, which may eliminate the power fluctuations (last from ten minutes to one hour), can be seen from the grid [2].

### 2.4.2 Offshore wind farms

The interest in the utilization of offshore wind power is increasing significantly in Europe. The reason is that the wind speed offshore is potentially higher than onshore, which leads to a much higher power production. A 10% increase in wind speed results theoretically in a 30% increase in power production. The offshore wind power potential can be considered to be significant. [7].

Different technologies used in three large offshore wind farms, an offshore wind farm HRA, an offshore wind farm ROA, and an offshore wind farm Middelgrunden are described as follow:

1) Nysted offshore wind farm

The wind farm consists of 72 BONUS 2.3 MW fixed speed, active-stall, wind turbines equipped with induction generators (165.6 MW installed capacity).

2) Middelgrunden offshore wind farm

The wind farm consists of 20 BONUS 2.0 MW fixed speed, active-stall, wind turbines equipped with induction generators (40 MW installed capacity).

3) Horns Rev offshore wind farm

The wind farm consists of 80 VESTAS-V80 2.0 MW variable speed, pitched control, wind turbines equipped with doubly-fed induction generators (160 MW installed capacity).

A forecast made by the Elkraft system (presently, it is Energinet.dk-east) [14] shows that it is technically possible for Denmark to get 50% of its power from wind generation by 2025. The possibility to reach this limit of wind power installation as set by the Danish government in 2025, aims at 4 GW of offshore wind farms of which the largest part should be installed in the western Denmark. Therefore, a lot more of large offshore wind farms will be installed in the western Denmark.

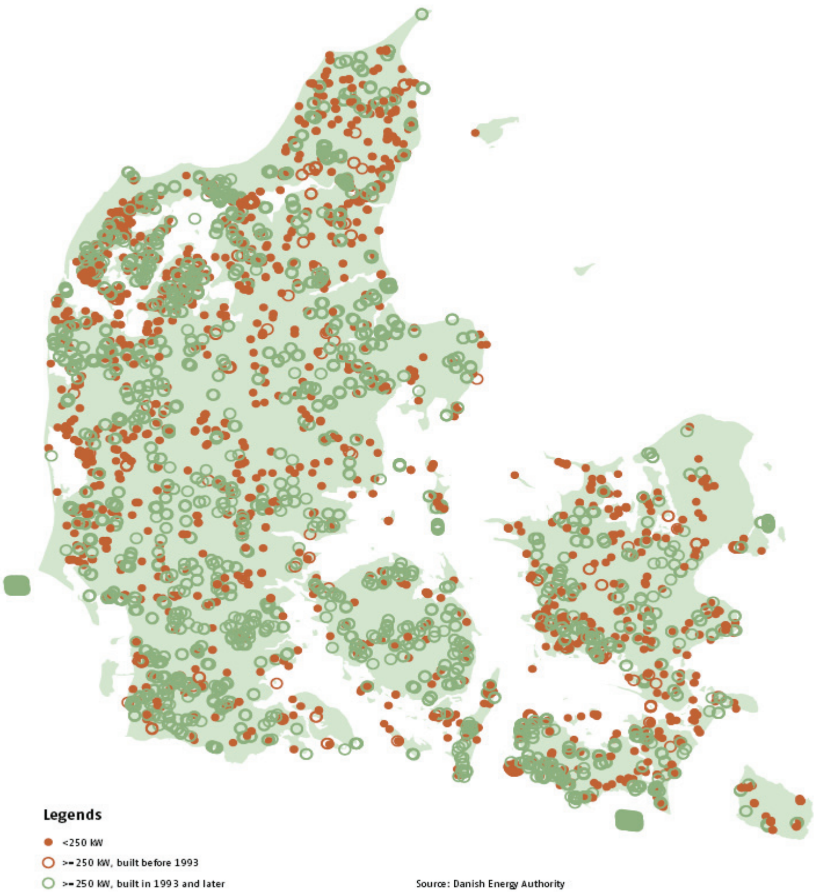


**Figure 2-5. Wind turbines in the Danish power system [3]**

# 2.5 System interconnections

Denmark is situated between the Nordel system and the UCTE system. The transmission capacities between the eastern Denmark (Energinet.dk-east) and its neighbouring countries are described in Table 2-5. The transmission capacities between the western Denmark (Energinet.dk-west) and its neighbouring countries are described in Table 2-6.

## 2.5.1 System interconnections with Nordel system

The western Danish power system is connected to the Nordel system via HVDC connections to Norway and Sweden. Power transaction with hour-by-hour "NEW Settlement Model" [2], may start at the beginning of each hour or, when preferred, at the beginning of at least each quarter within the given hour. The transaction ends at the end of each hour and then the new transaction may begin. A transaction must start with the largest required power exchange and may be reduced each quarter of an hour within the given hour.

**TABLE 2-5**
**TRANSMISSION CAPACITIES OF THE EASTERN DANISH POWER SYSTEM [10]**

| Connections | Transmission Capacities (MW) |
|---|---|
| Sweden (AC) | 1700 |
| Germany (HVDC) | 600 |
| Energinet.dk-west (HVDC) | 600 |

**TABLE 2-6**
**TRANSMISSION CAPACITIES OF THE WESTERN DANISH POWER SYSTEM [10]**

| Connections | Transmission Capacities (MW) |
|---|---|
| Sweden (HVDC) | 540 |
| Norway (HVDC) | 1040 |
| Germany (AC) | 1400 |
| Energinet.dk-east (HVDC) | 600 |

A transaction must not have any change in the direction of power flow. The characteristic time of the power ramp between different power levels of two different transactions may be 10 or 15 min. The power ramp between different power levels of two bids may be 15 min. [2]. It means that power exchange through the HVDC connections are made as hour by hour agreements, and there can only be some changes 3 times within an hour, and only in one direction. Therefore, the new settlement model introduces restriction on the use of the fast power control of the HVDC links.

## 2.5.2 System interconnections with UCTE system

The western Danish power system is connected to the UCTE synchronous area via 400 kV line to Germany. Long-term and short-term power balances of the Danish transmission system, and keeping the power balance of the system interconnection with Germany (the UCTE system) is the main issue for the western Danish power system operation. The rapid power fluctuation generated from offshore wind farms will contribute to deviation in the planned power exchange between the western Denmark and the UCTE system.

Beside, the power fluctuation introduced by wind farms, deviations from planned power generation, power consumption, and power exchange with the Nordel system contribute to the total deviation in the power exchange.

## 2.6 Great Belt Link connection

A Great Belt Link HVDC connection between the eastern and the western Denmark is planned as illustrated in Figure 2-6, as the eastern and the western Denmark are not electrically synchronized. Establishment of the GBL HVDC connection will make it possible to utilize the regulating power control incorporated in the eastern part of Denmark to work together with that established in the western Denmark.

The GBL connection is developed based on several reasons such as large changes to the Danish electrical system during the last 10 years with regard to wind power and DCHP units, one TSO Energinet.dk instead of two TSOs as Eltra and Elkraft system, and better power balance control with fast disturbance reserves and value of sharing disturbance reserves between eastern and western Denmark [14]. The cable would mean reduced requirements of reserves in the Danish electricity supply and also improve the scope for redressing imbalances in the power system between eastern and western Denmark. The cable would restrict any abuse by the electricity generators of their dominant market position. At the same time, the GBL will increase the robustness of the power supply in Denmark as it will give access to reserves from other parts of the country.

Energinet.dk plans a 600 MW cable link in the form of a traditional DC cable with converter stations as the eastern part and the western part of Denmark are not electrically synchronised. Conventional HVDC technology is chosen because the increased loss in a HVDC-VSC (Voltage Source Converter) does not justify the added value of the HVDC light technology. The capacity of 600 MW is planned for the GBL because the benefit is better suited for reserve reservation and future demand, and a larger unit size would increase the demand for reserves (the largest unit is 600 MW) [14].

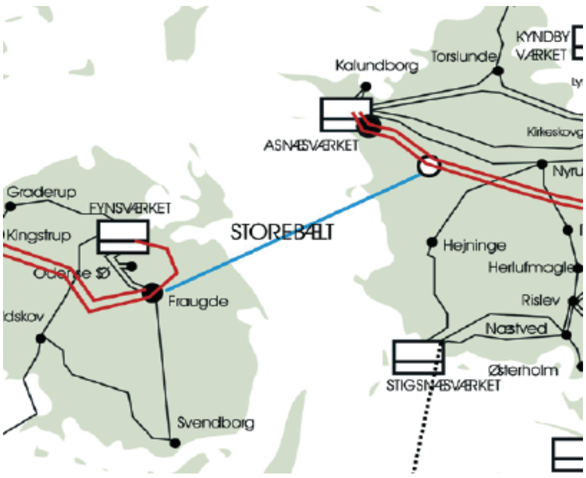


**Figure 2-6. The Great Belt Link HVDC connection between eastern part and the western part of Denmark [3]**

# 2.7 Challenges in Danish power system operation

System integration of large scale wind power is raising a long list of important issues that must be evaluated. On the large interconnected systems, the power balancing problem is one of the main challenges. The power fluctuations generated by wind farms at different weather conditions are of interest with respect to the needed regulating power. In Denmark, power fluctuation generated from the offshore wind farms may give a significant contribution to the deviation from the planned power exchange between the western Denmark and Germany, the UCTE system. These unscheduled power flows could reduce system stability and increasingly affect trading capacities.

On January 8th, 2005 there was a storm affecting the southern part of Scandinavia which caused high wind power production in west Denmark. The wind speed rose slowly to reach its climax rate in the afternoon [15]. Wind production smashed the plan just before the afternoon as the wind turbines started to cut-out due to excessive wind speed and the wind power production was reduced from 2000 MW to 100 MW as shown in Figure 2-7. Spinning reserve is needed to replace 1,700 MW wind power that disappeared in tact with the wind speed exceeding the critical speed [15]. It can be seen that the wind power production did not cut-out at the same instant due to the geographical distribution of the wind turbines; therefore the storm did not affect all of them simultaneously. In this situation, the balancing control was handled through the balancing market and by the regulating the HVDC link between Norway and Denmark from full export to full import. This example illustrate clearly that the Nordic power system can handle large amount of wind power fluctuation. With the increasing of large scale offshore wind farms in the Danish power system, the power balancing control issue would be more challenging.

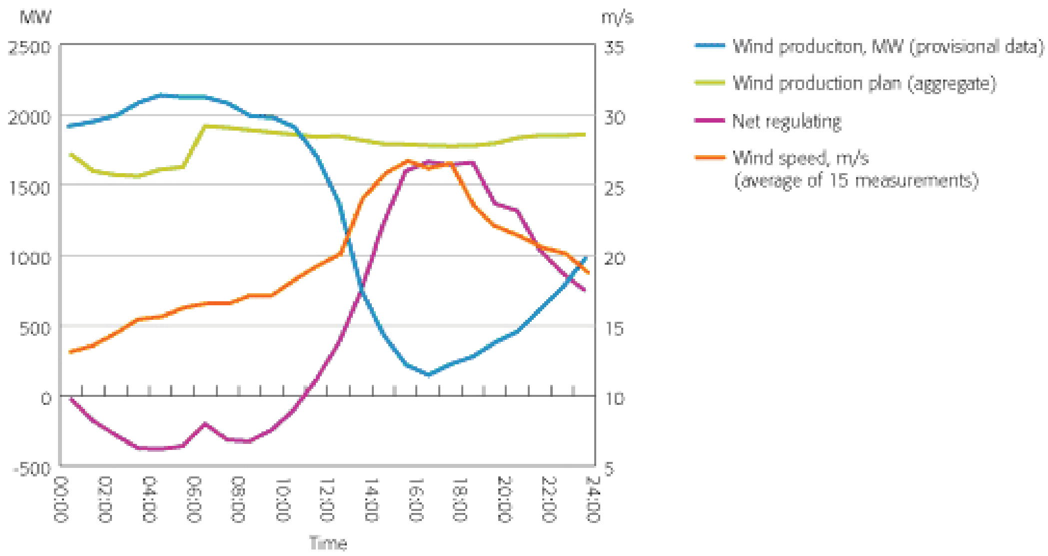


**Figure 2-7. Power fluctuations when the storm passed over the western part of Denmark on January 8th 2005 [15]**

# 2.8 Summary

In this chapter, an overview of the Danish power system is given. The general structure of the Danish power system is presented and discussed. It is indicated that the Danish power system is characterised by a large degree of incorporation of dispersed generations such as DCHP units, on-land wind turbines and offshore wind farms. The basic principles of power generating units which includes conventional power plants, distributed combined heat and power plants, wind turbines and wind farms are discussed.

The general working principle of the system interconnections with Nordel and UCTE systems and technical specification of the great belt link HVDC connection are also presented. The main concepts of conventional generating units and wind power generation in the Danish power system and their advantages are discussed and the concept of wind power generation in both on-land wind turbines and offshore wind farms, which depicts the dependence of the generated power on the wind speed, is presented. The challenge in Danish power system operation with regard to power balancing control issue is discussed.

It is expected that due to the large scale wind power penetration in Denmark, power fluctuation generated from wind turbines and wind farms may cause system impact on the Danish power system operation. The power balancing control between the western part of Denmark and the UCTE system is indicated here as the focus of this thesis.

# Chapter 3
# Modelling of Power System and Control

## 3.1 Introduction

In this chapter, an overview of the Danish power system model and an AGC system with wind power integration for long-term dynamic simulation is introduced. Power system simulation studies using the developed models and control strategies should be carried out in order to investigate the long-term system stability under the dynamic behaviour of the wind power sources.

In order to clearly define the application area of the model presented, this chapter shortly describes power system phenomenal and corresponding time scales that point out which simulation approach and time scale for the developed model in this chapter. This specific simulation approach is referred to as long-term dynamic simulation.

The contribution of this chapter is the modelling of the Danish power system and the AGC system with wind power integration for long-term dynamic simulation with regard to power balancing control. First the simplified model of the Danish power system and its components are presented and discussed. Then, the basics of load frequency control and the AGC system are described. The AGC system with large scale wind power integration is introduced and the control principles for power balancing control are discussed. Equations of the AGC system for long-term dynamic simulation including its controller have been described and combined into a model of the AGC system for long-term stability analysis.

Finally, the model is validated in long-term dynamic simulation in order to compare the simulation results with measurements and to investigate the influences of the participation factors of the AGC system. The summary of the Danish power system model and AGC system with wind power integration is also given.

## 3.2 Power system simulation time scale

The analysis of power systems is posed by the vast difference in frequency bands and time scales in which the various phenomena of interest occur. The phenomena of lightning transient, switching transient, transient stability take microseconds to milliseconds. These phenomena with time scales of 0 – 10 seconds can be indicated as short-term stability. The other phenomena that take several minutes or hours are substantial change in active power output of thermal power plants that can occur at a limited rate due to the generation rate constraint in mechanical and thermal stress limit and the changes in wind power generations as a result of fluctuated wind speeds. These phenomena with time scales of 10 seconds to a few minutes and a few minutes to 10's of minutes can be indicated as mid-term stability and long-term stability respectively [16].

Long-term stability focuses on the slow and longer duration phenomena that accompany large scale system upsets and on the resulting large, sustained mismatches between generation and consumption of active power. These phenomena include boiler dynamics of thermal units, automatic generation control, power plant control, etc. Figure 3-1 gives an overview of the ranges of consideration time scales and frequency bands.

The topic being interested in this research project is the impact of large scale wind power integration on power balancing control in the Danish power system. The shortest time constants in electrical power system are in millisecond, while the measurements of generations and loads time series of 30 seconds up to 15 minutes are used in the project. In order to observe the phenomena of interest, a relative long-term simulation is necessary. Therefore, an appropriate simulation approach has been developed which is referred to as long-term power system dynamic simulation.

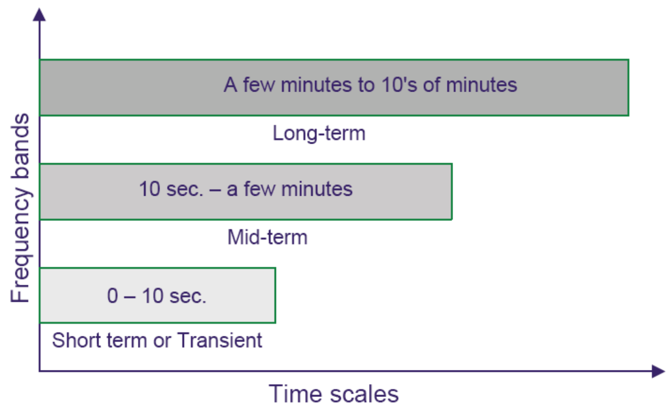


**Figure 3-1 Frequency bands and time scales of various types of stability**

## 3.3 Modelling of Danish power system

A generic model with a similarity to the Danish power system is set up. The Danish power system model which includes power generating units, loads and system interconnections for long-term dynamic simulation is presented. Power generating units in the Danish power system includes centralized thermal power plants, decentralized combined heat and power units, on-land wind turbines and off shore wind farms.

An overview of the power generating units is given here. In the centralized thermal power plant model, the secondary control and the thermal dynamic of the boiler for long-term stability analysis are included in the model. An aggregated DCHP plant model includes the power control with regard to taking part in the secondary control. An aggregated wind farm model with wind farm power control system including balance control, delta control, and power gradient control for the long-term dynamic simulation is implemented and developed. The system interconnections of the Danish power system include international interconnected system with the UCTE and the Nordel systems and the GBL HVDC connection between the eastern and the western Danish power systems are also included in the model. The total generic model is expected to be used to evaluate the active power balance control in long-term dynamic power system simulation with different control strategies at different load and production conditions.

The topic being interested in this project is the impact of large scale wind power integration on power balancing control and the secondary control of the centralized power plants and the DCHP units to reduce the imbalance caused by rapid power fluctuations generated from large scale wind farms. The frequency stability is not of interest in this project as the Danish power system is interconnected with the UCTE system. The system interconnections between the western Danish power system and the UCTE system are modelled as a slack-bus with the measurement of planned power exchange. With the use of slack bus, the deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{DEV}^{UCTE} = P_{GEN} - P_{LOAD} - P_{EXC}^{Nordel} - P_{PLAN}^{UCTE} \tag{3-1}$$

where $P_{DEV}^{UCTE}$ is the deviation from planned power exchange measured at the slack-bus, $P_{GEN}$ is power generations, $P_{LOAD}$ is the system load, $P_{EXC}^{Nordel}$ is the power exchange with the Nordel system, and $P_{PLAN}^{UCTE}$ is the planned power exchange with the UCTE system, as a measurement time series.

In this research project, performance of the balancing mechanisms can be assessed via measuring deviation from planned power exchange with system interconnection in different system control scenarios. The simulation study concept of this project is illustrated in Figure 3-2.

The topic being interested in this project is the impact of large scale wind power integration on power balancing control in the Danish power system. Therefore the Danish power system model can be reduced to a two bus-bar model, with different power generating units, such as thermal power plants, DCHP units, on-land wind turbines, offshore wind farms, and loads. Based on the two bus-bar model, no transmission network grid is needed. The model consists of both eastern Denmark and western Denmark. The system interconnections to neighbouring countries are also included in the model as shown in Figure 3-3.

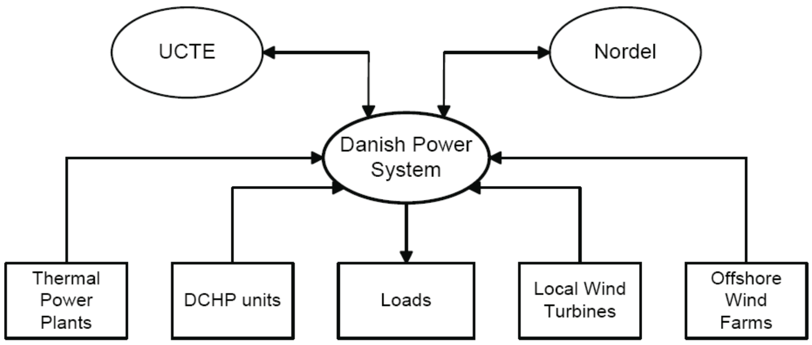


**Figure 3-2. The Danish power system simulation study concept**

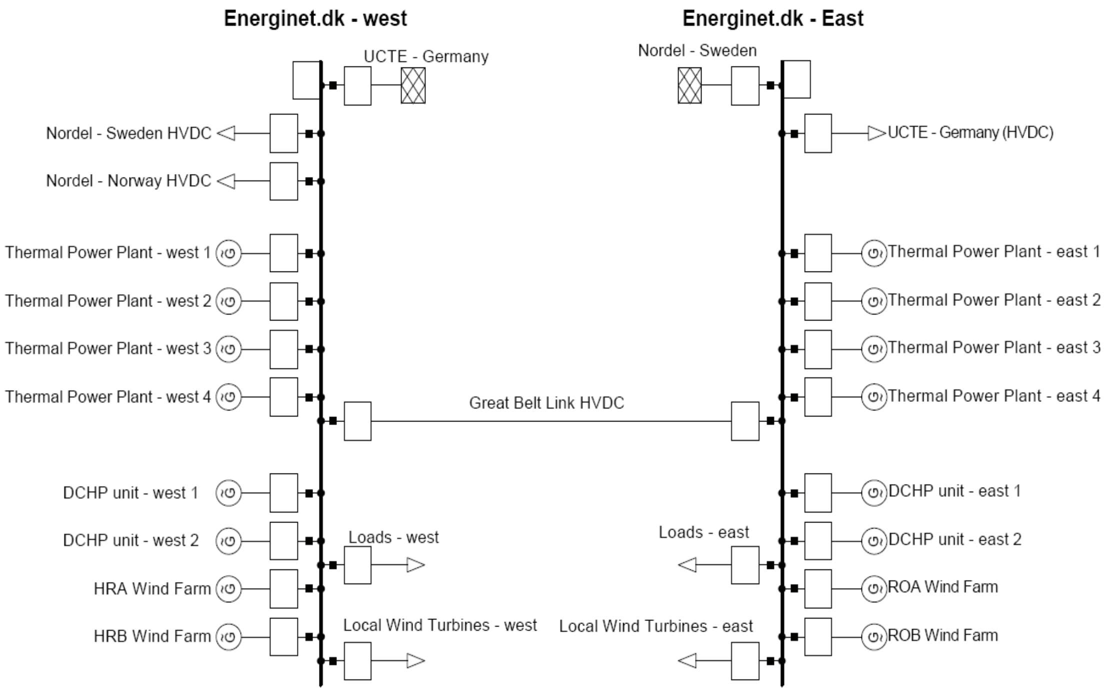


**Figure 3-3. The scheme of a generic model of the Danish power system**

# 3.4 Modelling of AGC system

With the increased large scale wind power penetration, the regulating power control of the Danish power system operated as presently are close to being exhausted as shown in the earlier studies in [3] and [17]. Such regulating power demand will indeed increase when the additional offshore wind farms are commissioned. This problem still requires a complete solution. Therefore, the proposed solution of an AGC system with the power balancing control is introduced.

Load Frequency Control (LFC) and the AGC system are used for the proposed models. The main objectives of LFC are to balance the power generation and the load consumption in the control area, to maintain the system frequency within required ranges and to keep the power exchange between areas at the scheduled values. LFC is organized in three levels. Primary control is performed by the speed governors of the power generating units, which vary load when the frequency changes to keep the instantaneous balance between power production and consumption. With primary control, a variation in system frequency greater than the dead band of the speed governor will result in a change in unit power generation. Generators are required to participate in this control by setting the droop according to specifications set by the system operator. Dynamics of primary control are in the time-scale of seconds.

Secondary control restores system frequency to its nominal value and also maintains the power interchange between areas in systems with several control areas. It adjusts the load set-point of the generators. Dynamics of secondary control are in the order of minutes. Tertiary control is an economic dispatch. It is used to drive the system as economically as possible and restore security levels if necessary [16], [18], [19]. The concept of AGC can include all automatic active power control actions except primary control. The AGC system introduces a secondary feed back loop as shown in Figure 3-4, while the speed governor based primary control can be found in most power generating units.

## 3.4.1 AGC system

AGC system is a control system having three major objectives [19]:

- To hold system frequency at or very close to a specified value
- To maintain the correct value of interchange power
- To maintain each unit’s generation at the nominal frequency value (50 Hz)

The AGC is designed and operated depending on the system requirements and the needs of the operator. The AGC system is allowed to ramp a unit from one output to another at a specific rate of change in output. This is most useful in bringing units up to the specified generation level and also for ramp following control of the total load ramping.

The AGC system is also operated taking into account that generating units can not change their output rapidly, especially for thermal power plants due to the generation rate constraint in mechanical and thermal stresses limit. The AGC system, as shown in Figure 3-5 represents an interesting scheme for controlling the power balance and for distributing the imbalance in an economical way in between selected power generating units. The Generation Control Error (*GCE*) is represented by the contribution from frequency deviations and the deviations from the power generation. The AGC computes unit set-points ($\Delta P_{set}$) and sends set point change commands to the selected units.

$$GCE = -\Delta P_{Gen} - \frac{\Delta f}{R} \tag{3-2}$$

where $\Delta P_{Gen}$ is the deviation of power generation from plan, $\Delta f$ is the frequency deviation in the system, *1/R* is total frequency bias.

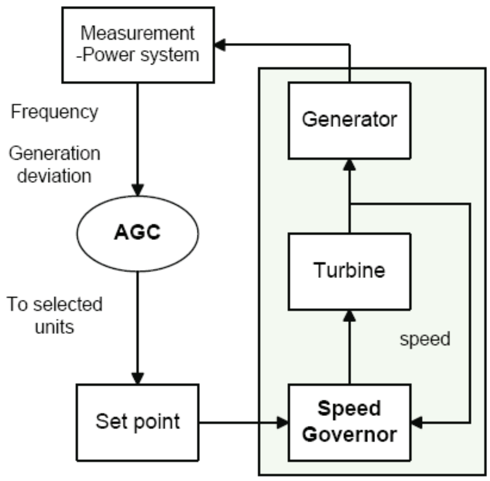


**Figure 3-4. AGC system and primary control**

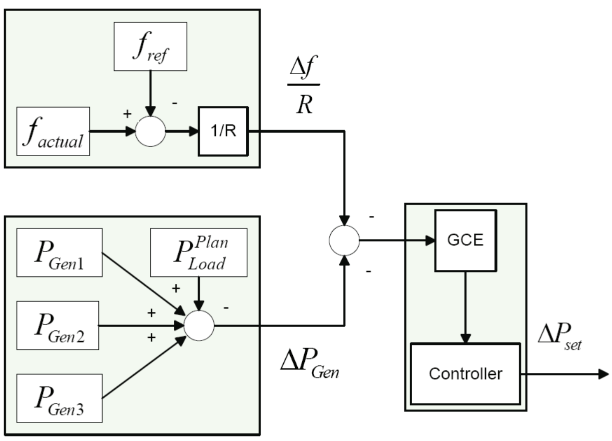


**Figure 3-5. AGC system control scheme**

### 3.4.2 AGC system with wind power integration

When implementing large scale wind farms, considerations should also include managing the fluctuated generation from wind turbines due to wind speed variations. Power system reliability can be effected by extreme wind conditions since they may result in loss of a large amount of wind power within minutes. Variability and controllability of wind power will affect the need for the secondary reserve. If thermal power production is replaced by wind power, this will have an effect on the system reliability and system stability [20]. This effect from the production of the wind farms has to be considered. Therefore, wind farms should be integrated in the AGC system for power balancing control.

The principle of AGC has been described earlier and the modifications needed for controlling wind power is now presented. Due to the wind speed variations and also the variations in wind power generation, it is important to include this unstable generation input in the AGC system. The control scheme is modified by an extra control input path representing the actual wind power generation and the planned wind power production (forecasted wind power production).

A model of the AGC system with wind power integration for dynamic power system simulation in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources is developed. The implementation of an AGC system model for power and frequency control simulation can be found in [21]. Figure 3-6 presents the scheme of an AGC system which includes large scale wind farms and the secondary control from conventional thermal power plants and the additional secondary control from DCHP units for maintaining the power balance.

For AGC purposes, the variations in wind generation are measured at the point of common coupling (PCC). The measurement is send to the dispatch centre and the control system. The deviation in power generations, that is deviation in actual wind power generation from planned wind power and the deviation from planned power exchange with the system interconnections, contributes to GCE, and is then distributed according to participation factors (*pf*) among the selected power generating units under the AGC system.

In this model, the GCE is now represented by the contribution from frequency deviations from thermal power generating units, the deviations from the wind power generation from planned wind power, and the deviations from planned power exchange with the UCTE system. In case of several wind farms, the generation from each wind farm must be send to the control centre. The GCE presented hereby reflects the deviation of wind power generation and the deviation from planned power exchange with the UCTE system.

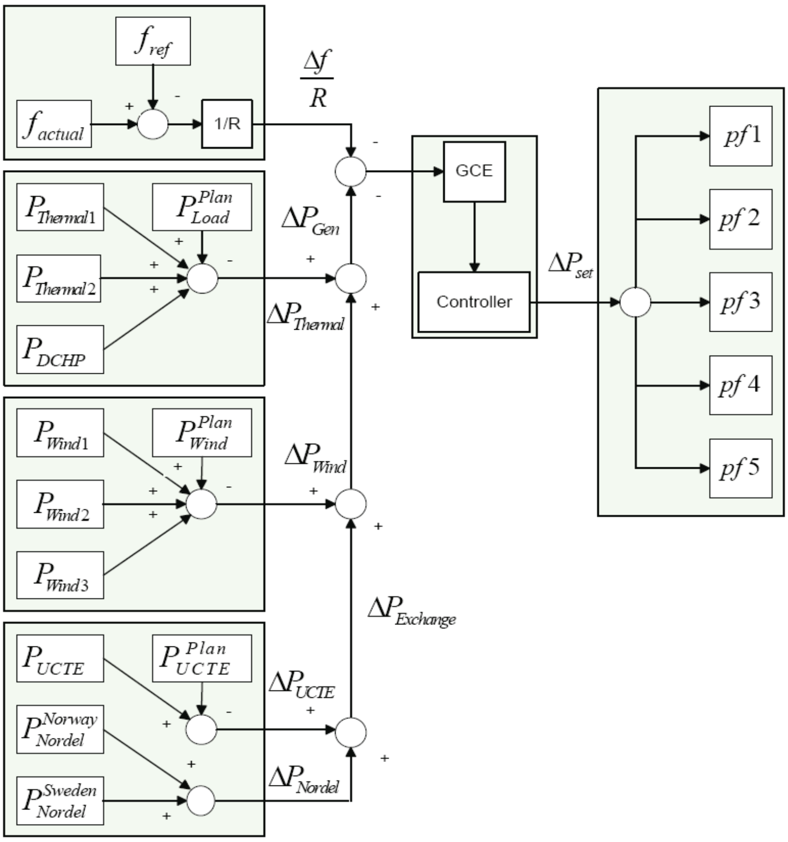


**Figure 3-6. AGC system with large scale wind power integration**

Based on measurement of system frequency and unit generations, the AGC computes unit set-points $\Delta P_{set}$ and sends set point change commands to the selected power generating units. The selection is based on the generating units' ramping capability and the regulating electricity market conditions given here by the *pf*. This set-point will be used until the next execution of AGC, typical sample times ($T_{AGC}$). This is mathematically written as:

$$GCE = -\Delta P_{Gen} - \frac{\Delta f}{R} \tag{3-3}$$

$$\Delta P_{Gen} = \Delta P_{Thermal} + \Delta P_{Wind} \tag{3-4}$$

$$\Delta P_{Thermal} = \sum P_{Thermal} - P_{Load}^{Plan} \tag{3-5}$$

$$\Delta P_{Wind} = \sum P_{Wind} - P_{Wind}^{Plan} \tag{3-6}$$

$$\Delta P_{set} = K * GCE + \frac{1}{T}\int GCE \tag{3-7}$$

$$\sum P_{Thermal} = P_{Thermal1} + P_{Thermal2} + \ldots + P_{DCHP} \tag{3-8}$$

$$\sum P_{Wind} = P_{Wind1} + P_{Wind2} + P_{Wind3} + \ldots \tag{3-9}$$

$$\Delta P_{UCTE} = P_{UCTE} - P_{UCTE}^{Plan} \tag{3-10}$$

$$\Delta P_{Nordel} = P_{Nordel}^{Norway} + P_{Nordel}^{Sweden} \tag{3-11}$$

$$\sum_{i=1}^{n} pf = pf_1 + pf_2 + pf_3 + \ldots + pf_n = 1 \tag{3-12}$$

where *GCE* is the Generation Control Error, $\Delta P_{Gen}$ is the deviation power generation from plan, $\Delta P_{Thermal}$ is the thermal power deviation from plan, $\Delta P_{Wind}$ is the wind power deviation from plan, $\Delta f$ is the frequency deviation in the system, *1/R* is total frequency bias, $\Delta P_{set}$ is correcting power set-point for all selected units, *K* is the proportional factor (gain), *T* is the integration time constant, $\Sigma P_{Thermal}$ is the total power generations except wind power, $\Sigma P_{Wind}$ is the total wind power generations, $P_{DCHP}$ is the power generation from DCHP units, $P_{Load}^{Plan}$ is the power consumptions (loads), $P_{Wind}^{Plan}$ is the planned wind power (forecasted wind power), $\Delta P_{UCTE}$ is the deviation from planned power exchange with UCTE, $\Delta P_{Nordel}$ is the power exchange with Nordel.

A time series data for the *pf* values can be used for the specific case study, as the centralized power plants are operated according to the electricity market conditions. The *pf* values can be set to 0 when the generating units are not participated in the AGC system, or when the generating unit is off from the system due to the shut-down time or maintenance. The *pf* value for each power plant can be varied from 0.0 to 1.0 with regard to 0% to 100% correspondence to the regulating power control provided from the generating units.

The summation of the *pf* values of all power generating units in the AGC system should have a maximum of one. The deviation in wind power generation, that is deviation in actual wind power generation from planned wind power production, contributes to GCE, and is then distributed according to the *pf* values among the selected power generating units under the AGC system. The range of *pf* values for different power generating units in the AGC system are shown in Table 3-1.

TABLE 3-1
PARAMETERS FOR POWER BALANCE CONTROL IN AGC SYSTEM

| Parameters | Control Objects | pf |
|---|---|---|
| pf1 | Thermal power plant 1 | 0 - 1.0 |
| pf2 | Thermal power plant 2 | 0 - 1.0 |
| pf3 | Thermal power plant 3 | 0 - 1.0 |
| pf4 | Thermal power plant 4 | 0 - 1.0 |
| pf5 | DCHP unit in AGC | 0 – 0.2 |
| pf6 | Wind farm A | 0 – 0.1 |
| pf7 | Wind farm B | 0 – 0.1 |

# 3.5 Generations and loads

## 3.5.1 Loads

Figure 3-7 shows the demand for electricity varies significantly during the day. Electricity has to be produced at the same pace as the demand as it cannot be stored. Generally, the demand is lowest in night hours and highest in day hours. The working days show the largest difference between day and night. Moreover, the demand is higher in working days since industry needs power. The demand for electricity also depends on the seasons. Winter loads are higher than summer loads [3]. In this project, load time series data is used for long-term power system dynamic simulation. The load time series data for one week in energinet.dk-west system is illustrated as shown in Figure 3-8.

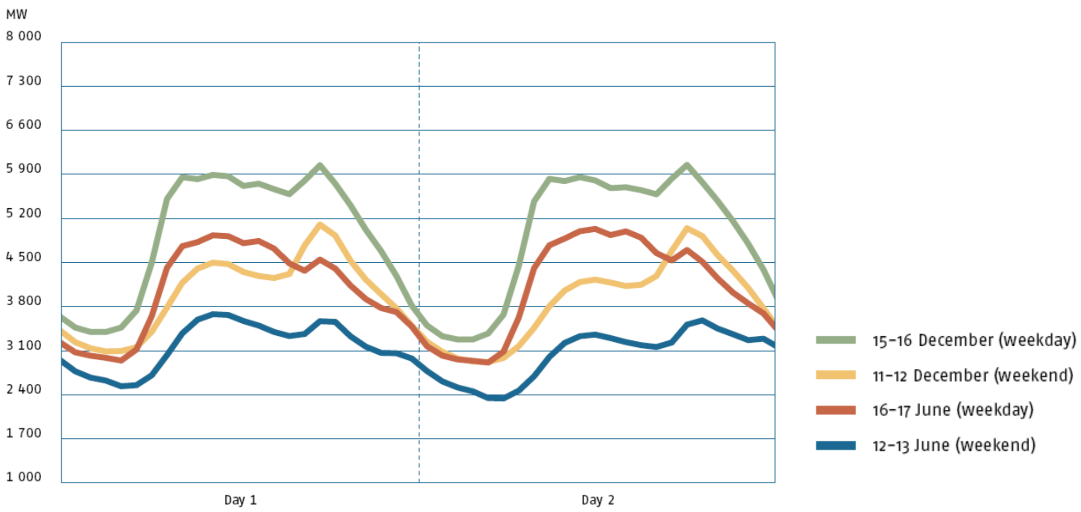


**Figure 3-7. The variation of electricity demand in Denmark during the day [3]**

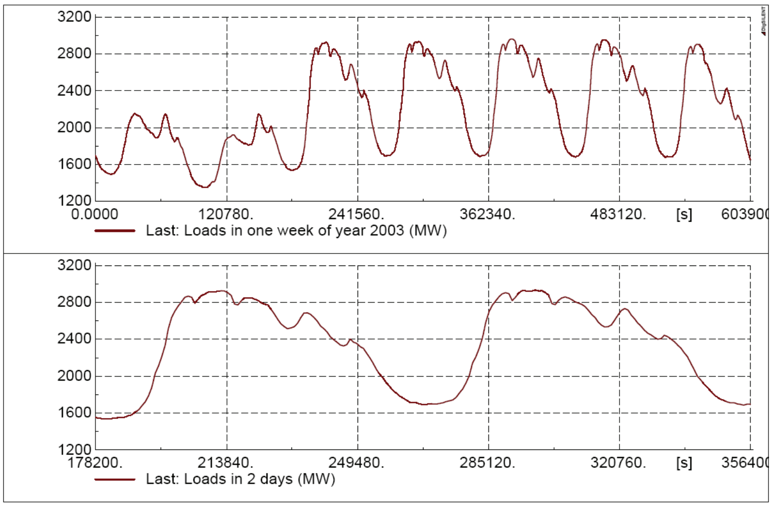


**Figure 3-8. Load time series in Energinet.dk-west during one week in year 2003 [10]**

### 3.5.2 Time series data

Time series data of generations and loads of the Danish power system are needed for the validation of the developed AGC system model with power balancing control. Time series data of centralized thermal power generations, DCHP generations, wind power generations, loads, power exchange with the Nordel system, and power exchange with the UCTE system are illustrated in Figure 3-9, Figure 3-10, Figure 3-11, and Figure 3-12 respectively. All time series data of generations, loads and power exchange are provided by Energinet.dk [10].

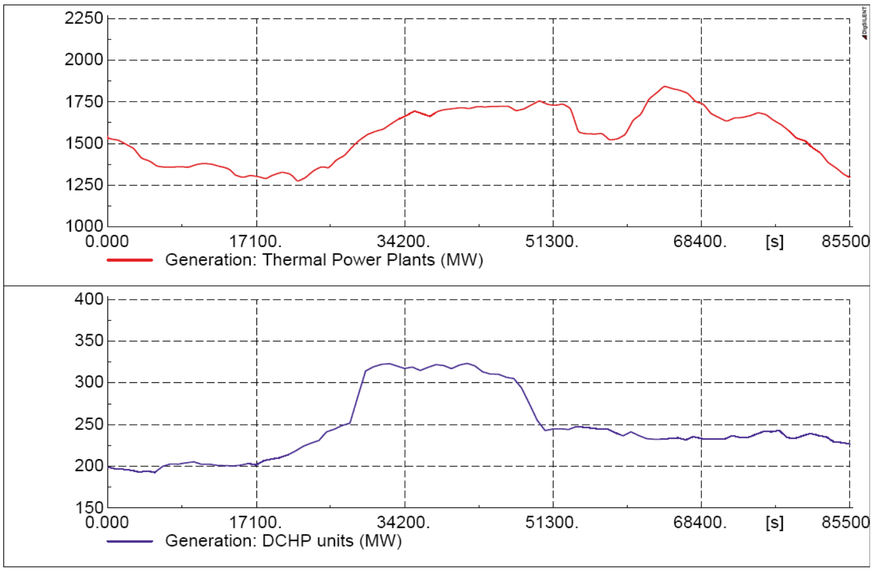


**Figure 3-9. Time series data of centralized thermal power generations (above) DCHP generations (below)**

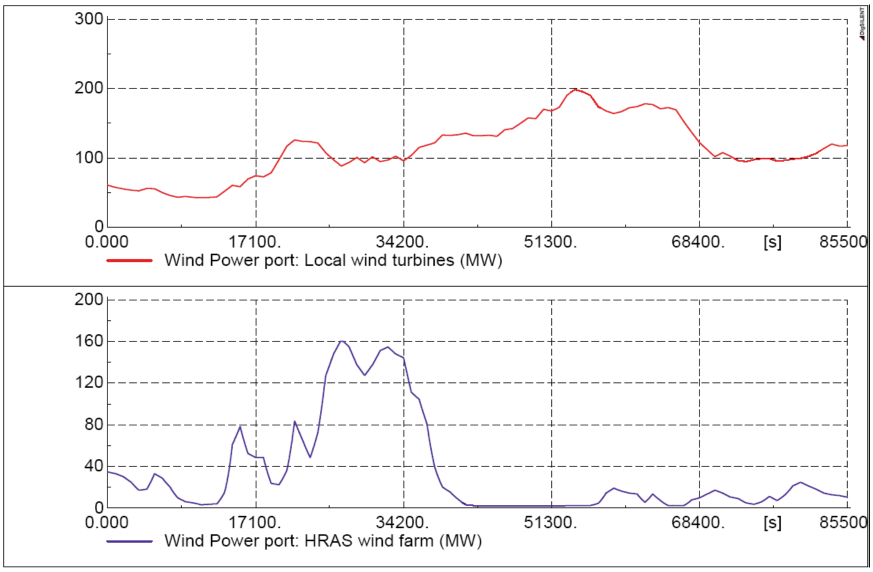


**Figure 3-10. Time series data of on-land wind power generations (above) and time series data of offshore wind power generations (below)**

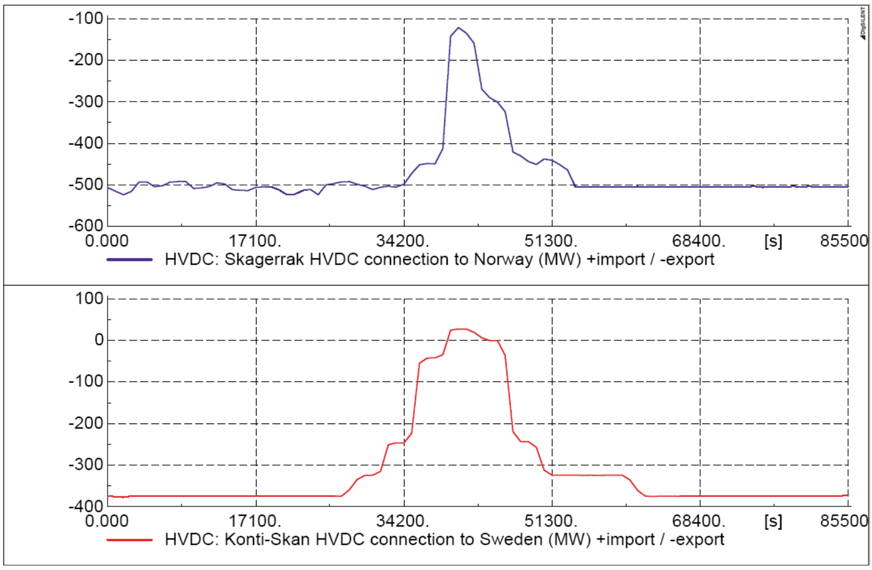


**Figure 3-11. Time series data of power exchange with, the Nordel system, Norway (above) and Sweden (below)**

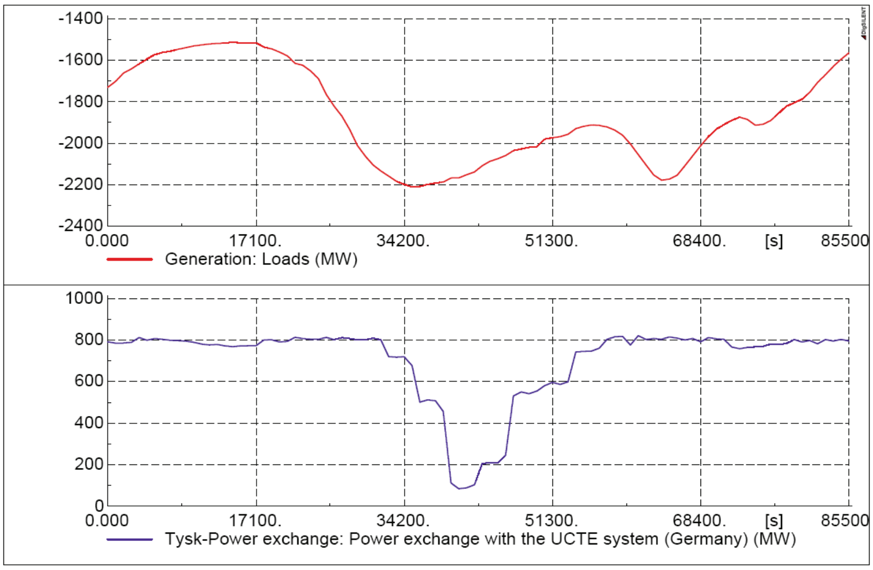


**Figure 3-12. Time series data of loads (above) and time series data of power exchange with, the UCTE system, Germany (below)**

According to the time series data provided from Energinet.dk. The summation of the measurements of generations, power exchanges with other systems and loads is not equal to zero, due to the loss in transmission system and the error in measurement.

### 3.5.3 Simulation studies

In this simulation study, the thermal power plants are separated into 4 groups with different ramp rate capabilities as shown in Table 3-2. When deviations from the planned power exchange are observed, the AGC system will adjust the available power production in the available power generating units. The overall model includes the power gradient limit and the necessary time constants of the processes. With the use of the AGC system, the deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{DEV}^{UCTE} = P_{MEAS} - P_{PLAN} - P_{Ctrl} \tag{3-13}$$

The deviations power ( $P_{DEV}^{UCTE}$ ) between the measured power ($P_{MEAS}$) and the planned power exchange ($P_{PLAN}$) with the UCTE system shall be minimized by the power balancing control ($P_{CTRL}$).

The dynamic simulation of the aggregated thermal power plant model, as will be described in chapter 4, with the given time series data of DCHP generations, wind power generations, loads, and power exchange with the Nordel system, on a day in 2003 is demonstrated. The power balancing control model applied in this analysis has been successfully validated against the measured value as shown in Figure 3-13.

TABLE 3-2
RAMP RATE LIMITER AND UNIT TIME RESPONSEOF THERMAL POWER PLANTS

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (sec.) | Participation factor (pf) |
|---|---|---|---|---|---|---|---|
| **Plant 1** | 1738 | 2 | 2 | 4 | 2 | 180 | 0.3 |
| **Plant 2** | 700 | 1.5 | 2 | 4 | 2 | 180 | 0.1 |
| **Plant 3** | 392 | 2 | 2 | 8 | 2 | 180 | 0.5 |
| **Plant 4** | 625 | 2 | 2 | 4 | 2 | 300 | 0.1 |

This analysis has shown the secondary control capability of the thermal power plants which nearly eliminate the deviation from the planned power exchange with the UCTE system. In the simulation study, complying with the total regulating power therefore implies that the deviations in the power exchange with the UCTE system may be kept within an acceptable limit, but not to be completely eliminated.

Simulation result of power generation from 4 aggregated power plant models with different ramp rate capabilities and participation factors, as shown in Table 3-2, operated with the developed AGC system model is shown in Figure 3-14. The responses of aggregated power plant models are investigated. It can be seen that the responses of plant 2 and plant 4 with *pf* = 0.1 is almost constant, while the generations of plant 1 with *pf* = 0.3 and plant 3 with *pf* = 0.5 give higher units' responses.

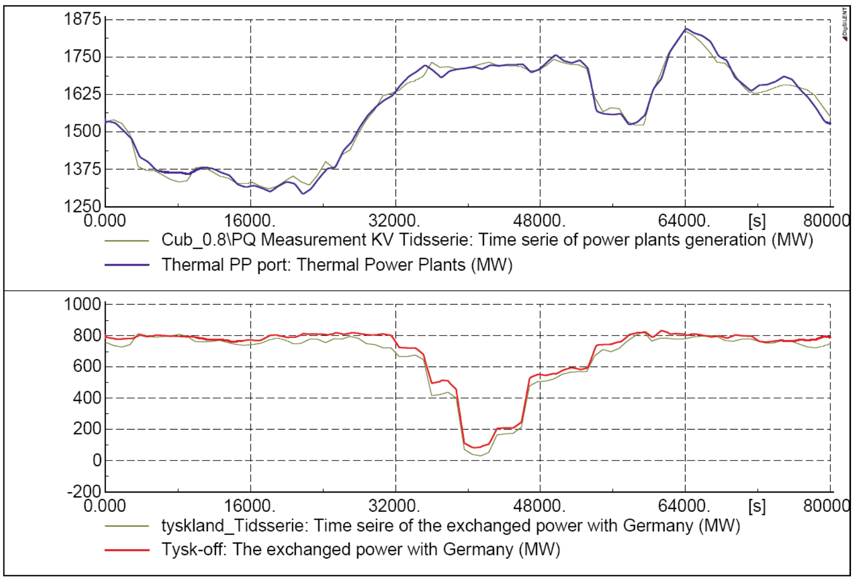


**Figure 3-13. Comparison between the measured value (grey color) and the simulation results of a) power generation from thermal power plants (blue color, above), and b) power exchange with Germany (red color, below)**

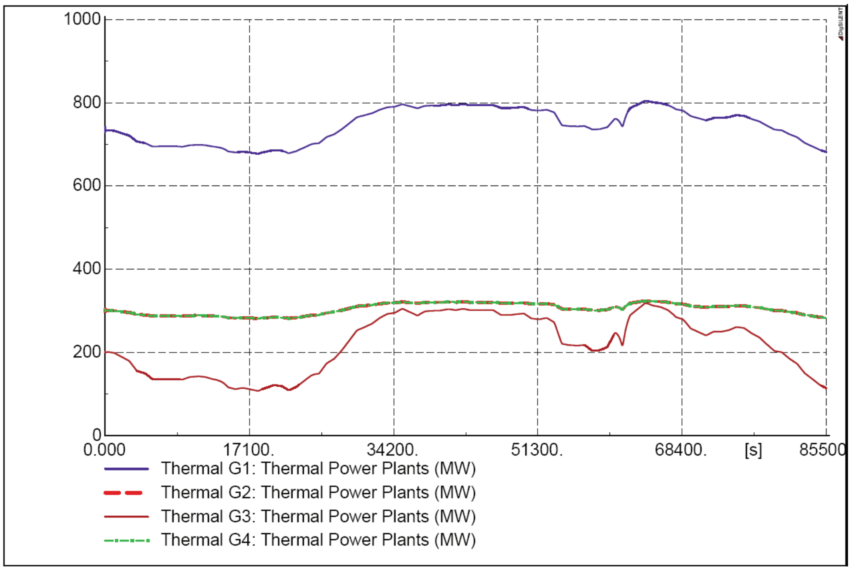


**Figure 3-14. Power generation from 4 thermal power plants with different ramp rate, boiler time constant and participation factors from AGC system**

# 3.6 Summary

The topic covered in this chapter is the development of the power system model and control system for long-term dynamic simulation. In this chapter, an overview structure of the Danish power system model is presented. The contribution of this model in this chapter is indicated. This model is particularly developed for use in power system long-term dynamic simulation and contains all subsystems that are of importance in this study.

The main part of this chapter consists of a description of the AGC model. An AGC system concept and the AGC system model with wind power integration are presented. The detailed description of the AGC model is provided. The structure of the AGC model with wind power integration is depicted and the equations of each subsystem are given. The implications of the assumptions on which the power system dynamic simulation approach is based on, taking into account the simplification of these equations.

The developed model is intended to use for the calculation of the imbalance in power exchange with the interconnected UCTE system. This model can also be used to investigate the system reliability and system adequacy with regard to the deviation of power exchange with the interconnected systems at different loads and generations. From the simulation study, it can be seen that sufficient amount of regulating power to compensate for such intense power fluctuations generated from large scale wind farms is one of the keys for maintaining the power balance and efficient operation of the power system.

Finally, the model is used in a long-term dynamic simulation in order to compare the simulation results with measurements and to investigate the influences of the participation factors of the AGC system. The developed AGC system model has been successfully validated against the measurement. It can be observed that the model is reasonably accurate and can be used in long-term dynamic simulations. The investigation of the influence of the participation factors of the AGC system is carried out. It can be seen that the degree of power generating units' responses are depend on the participation factor. This gives confidence in the developed AGC model and shows that the result of the applied simulation is acceptable.

# Chapter 4

# Modelling of Power Generating Units

## 4.1 Introduction

In this chapter, models of domestic power generating units in the Danish power system that were described in Chapter 3 are derived. For model development, it must take into account its intended application. The developed model should neither become too complex which would make the calculation cumbersome and time consuming, nor too simple which render the model inapplicable and give unreliable results.

This project focuses on the capability of the secondary control of the thermal power plants, together with the secondary control provided from the DCHP units to reduce the imbalance caused by rapid power fluctuations generated from large scale wind farms. The objective of this project is to evaluate the results from simulation studies based on several study scenarios in order to analyze the power system long term stability with regard to power balancing control.

This chapter continues with the development of models for representing regulating power control for the AGC system in power system dynamic simulations. The various subsystems of each of the power generating units and the corresponding equations are primarily described. In the thermal power plant model, the secondary control includes the thermal dynamic of the boiler for a long term stability analysis. The developed DCHP unit model includes the power control with regard to taking part in the secondary control. In an aggregated wind farm model with wind farm power control system, a power controller for the wind farms including balance control, delta control, and power gradient control for the long-term dynamic simulation is included in the model.

The total generic model is expected to be used to evaluate the active power balance control and long-term system stability with various control strategies at different loads and production conditions. Finally, simulation results obtained from the models are compared to measurements and detailed model. From a comparison of the measurements and the simulations it is concluded that the models are reasonable accurate and can be used for presenting for power generating units in long-term dynamic simulation.

# 4.2 Centralized thermal power plant model

Most of the centralized thermal power plants in Denmark are coal-fired CHP plants that can extract steam for heat production and have an operating domain between 20% and full power load without heat production [2], [8], [22]. According to the centralized thermal power plant specifications, in Table 4-1 and Table 4-2, the thermal power plants have a ramping capability of full load per minute in different operating ranges and different units' time response. These power plants should be separated into groups performing slow and relatively fast secondary control respectively with regard to their ramp rate limiter and units' time response.

**TABLE 4-1**
**TECHNICAL DATA OF THERMAL POWER PLANTS IN EASTERN DENMARK** [10]

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Min. production (MW) | Time response (min.) |
|---|---|---|---|---|---|---|---|
| Amager | 479 | 2 | 2 | 4 | 2 | 45 | 3-4 |
| Asnaes | 1057 | 1.5 | 2 | 4 | 2 | 150 | 3-4 |
| Avedoere | 820 | 2 | 2 | 4 | 2 | 70 | 3-4 |
| H.C. Oersted | 274 | 2 | 2 | 4 | 2 | 40 | 3-4 |
| Kundby | 646 | 2 | 2 | 4 | 2 | 130 | 5-6 |
| Stigsnaes | 408.5 | 2 | 2 | 8 | 2 | 60 | 3-4 |
| Svanemoelle | 166 | 2 | 2 | 4 | 2 | 25 | 3-4 |

**TABLE 4-2**
**TECHNICAL DATA OF THERMAL POWER PLANTS IN WESTERN DENMARK** [10]

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Min. production (MW) | Time response (min.) |
|---|---|---|---|---|---|---|---|
| Fynsværket B3 | 246 | 2 | 2 | 4 | 2 | 40 | 3-4 |
| Fynsværket B7 | 360 | 2 | 2 | 4 | 2 | 45 | 3-4 |
| Studstrup B3 | 350 | 1.5 | 2 | 4 | 2 | 35 | 3-4 |
| Studstrup B4 | 350 | 1.5 | 2 | 4 | 2 | 35 | 3-4 |
| Nordjyllands B2 | 285 | 2 | 2 | 4 | 2 | 57 | 3-4 |
| Nordjyllands B3 | 380 | 2 | 2 | 4 | 2 | 76 | 3-4 |
| Skærbærværket B3 | 392 | 2 | 2 | 8 | 2 | 78.4 | 3-4 |
| Enstedværket B3 | 625 | 2 | 2 | 4 | 2 | 125 | 5-6 |
| Esbjergværket B3 | 378 | 2 | 2 | 4 | 2 | 75.6 | 3-4 |

In chapter 2, it can be seen from Table 2-1 and Table 2-2 that all of the centralized power plants are based on steam turbine technology. Therefore, an aggregated model of a centralized thermal power plant with steam turbine technology should be developed. An aggregated centralized thermal power plant model is implemented and developed with regard to the boiler dynamic and secondary control.

From Table 4-1 and Table 4-2, the centralized thermal power plants in Denmark are divided into 4 groups based on their ramp rate capability and boiler time constant. Thermal power plants in the eastern Denmark are divided into the following groups. Amager, Avedoere, H.C. Oersted, and Svanemoelle are grouped as Plant 1. Asnaes is modelled as Plant 2. Stignaes is modelled as Plant 3. Kundby is modelled as Plant 4. In the western Denmark, power plants are also divided into the following groups. Fynsværket B3/B7, Nordjyllands B2/B3, and Esbjergværket are grouped as Plant 1. Studstrup B3/B4 is modelled as Plant 2. Skærbærværket is modelled as Plant 3. Enstedværket is modelled as Plant 4. Therefore, the centralized power plants are developed into 4 groups as aggregated power plant models which have different ramp rate and units' time response as shown in Table 4-3 and Table 4-4.

**TABLE 4-3**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN EASTERN DENMARK**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (min.) |
|---|---|---|---|---|---|---|
| Plant 1 | 1739 | 2 | 2 | 4 | 2 | 3-4 |
| Plant 2 | 1057 | 1.5 | 2 | 4 | 2 | 3-4 |
| Plant 3 | 408.5 | 2 | 2 | 8 | 2 | 3-4 |
| Plant 4 | 646 | 2 | 2 | 4 | 2 | 5-6 |

**TABLE 4-4**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (min.) |
|---|---|---|---|---|---|---|
| Plant 1 | 1684 | 2 | 2 | 4 | 2 | 3-4 |
| Plant 2 | 700 | 1.5 | 2 | 4 | 2 | 3-4 |
| Plant 3 | 392 | 2 | 2 | 8 | 2 | 3-4 |
| Plant 4 | 625 | 2 | 2 | 4 | 2 | 5-6 |

### 4.2.1 Aggregated thermal power plant model

The process of modelling a power plant may be approached from different points of view, depending on the purpose for which the model is intended. For long-term dynamic simulation, an aggregated thermal power plant model is needed where it is necessary to investigate the dynamic characteristic of the thermal boiler that can affect the power system performance during and following a disturbance such as loss of generations and loads. This chapter presents the development of an aggregated thermal power plant model for long-term dynamic simulation. The model is developed to be used for AGC purpose, so it has to deal with time constant in several seconds up to minutes. This model can be used to estimate the power response for the power balancing control, taking into account the specific and unavoidable characteristic of a centralized thermal power plant. The response of a conventional thermal power plant can at times be an important variable affecting the dynamic performance of electrical network.

When a large scale system is viewed as one system rather than a group of interconnected subsystems, the fast components of the large scale system become negligible compared to the slow components when a large time constant is considered. The general diagram of an individual centralized power plant is shown in Figure 4-1. The generic model can be used for long-term dynamic simulation when considering the dynamics of the boiler and the secondary control capability. For this purpose, the model consists of a speed governor, a thermal boiler, a boiler turbine control and a steam turbine. The model is based on simplifications of the steam turbine controls and dynamics with regard to the dynamics of the steam supply system and the effect of the various modes of the overall boiler turbine control, based on the study in [23] and [24]. The fuel dynamics is omitted from the boiler pressure effects model for the long-term dynamic simulation. Therefore, this model is put under the pressure/flow effects only. The actual performance will depend on many factors such as the type of plant, the characteristic of the boiler controls and the operational mode which will affect the steam turbines dynamic performance in the total unit response.

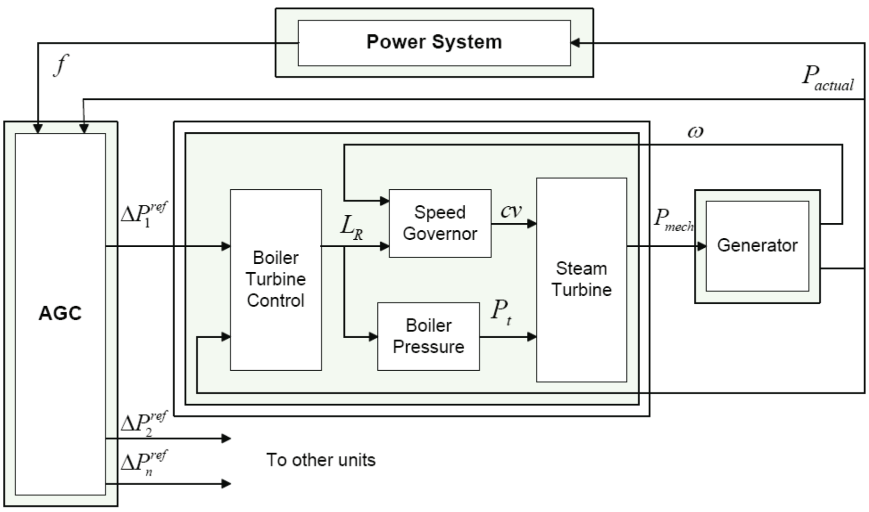


**Figure 4-1. Block diagram of the generic thermal power plant model**

The development of the model requires a compromise between making substantial simplification to reduce computation effort and maintaining the necessary adequacy to be able to predict the unit's influence on the system dynamic behaviour. The turbine model defines mechanical power ($P_{mech}$) as function of main steam pressure ($P_t$) and control valve flow area ($cv$). The speed governor model details the turbine control logic in response to change in load reference ($L_R$), and generator speed ($\omega$). The boiler turbine control block develops the load reference ($L_R$) input to the speed governor in response to the actual power generation ($P_{actual}$) and the power reference ($\Delta P^{ref}$) set by the AGC system. The parameters of an aggregated centralized power plant model are provided in Appendix B.

***a) Boiler turbine control model***

The boiler turbine control, as shown in Figure 4-2, is designed to regulate the valve pressure, but the controlled boiler response is not fast enough to compensate for pressure variations due to movement of governor-controlled valves. It can be assumed that a pressure change dependent on the boiler time constant in the boiler tubes from a constant pressure point to the valves. A signal indicative of the load is established by integrating the AGC signal $\Delta P^{ref}$ and the actual power $P_{actual}$. This signal forms the unit desired generation $L_R$, used to drive the turbine valve in a closed loop to match the actual generation to the desired generation, and to provide a feed forward signal to the boiler input as shown in Figure 4-1.

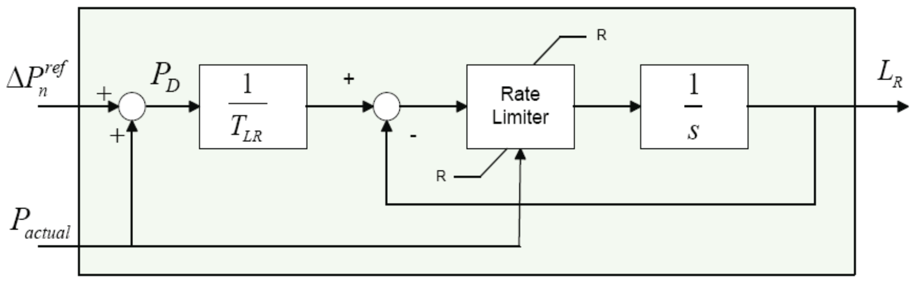


**Figure 4-2. Boiler turbine control model**

In the steam turbine system, due to thermodynamic and mechanical constraints, there is a limit to the rate at which its output power can be changed. This limit is referred to as generation rate constraint (GRC) and steam temperature control which is not directly included in the model. However, the rate limiter of the power output control with the specific parameters with regard to the limit of GRC and steam temperature control is included in this model. The actual measured MW is sent to the ramp rate limit controller to set the specific ramp rate with regard to actual operation status which integrates into a change in the turbine load reference $L_R$. The ramp rate limit parameters of aggregated thermal power plants are shown in Table 4-3 and Table 4-4. Thermal power plants are operated with the sliding pressure control mode, as will be described in section e. The power output to the turbine therefore follows the changes in the boiler steam generation as caused by changing in input to the boiler [25].

***b) Speed governor model***

The control logic that governs the positioning of *cv* is very specific to the type of the particular turbine, although the basic requirements are quite generic. The general requirements cover speed regulation under normal load change duty (primary speed control). The turbine speed governor model, as shown in Figure 4-3, can usually be generic when limited to primary control and secondary control. The inputs to the particular logic are speed deviation ($\Delta\omega$) and load reference $L_R$ signals.

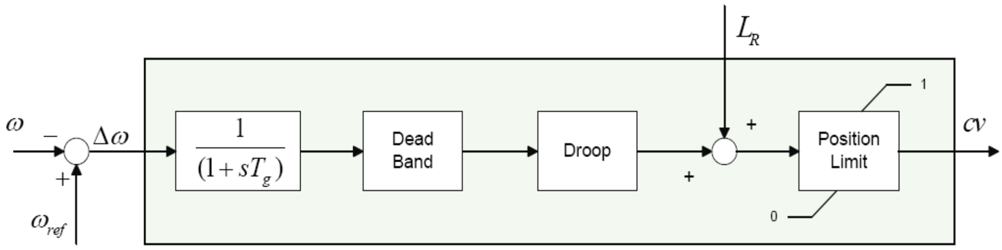


**Figure 4-3. Generic speed governor model**

A dead-band is included in the model, and is inserted due to imperfections of the mechanical equipment or could also be deliberately introduced to avoid excessive movement of steam valve (*cv*) due to continuous system frequency deviation avoiding consequential perturbations to the boiler controls. The load reference $L_R$ as a function of an AGC power set-point $\Delta P^{ref}$ and the actual power generation $P_{actual}$, is combined with the increments due to speed deviation to obtain the *cv*.

However, the secondary control is the only concern in this project, the primary control in the governing block is therefore omitted. Plant load is varied by ramping the steam supply pressure up and down using the boiler turbine control. Due to the operation in sliding pressure control mode and the primary control is omitted, the turbine valves are fixed in predefined fully opened position, and thereby $cv = 1.0$.

***c) Boiler model***

For a realistic study covering a long time frame, practical limits on the rate of the turbine output, and a delay associated with stored energy of steam in the boiler have to be included in the model. The process physics of a boiler can be visualized as shown in Figure 4-4, showing an equivalent lumped volume storing steam at an internal pressure labelled drum pressure in series, as $b_1$, $b_2$ and $P_t$. Firing and steam generation delays are represented by the time constant. Variation of drum pressure as steam production and consumption is also characterized by boiler time constant. The simplified boiler model for long-term dynamic simulation is developed based on the study in [26].

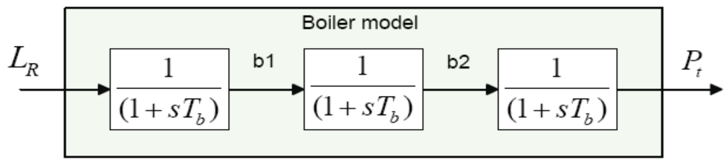


**Figure 4-4. Boiler model**

This boiler model is suitable for the time range in several seconds up to minutes. However, this boiler model does not fully represent small change (less than few %) due to the difference between steam generation from the water-walls and steam flow out of the storage volume in the detailed boiler model in [24]. The low order boiler model is used in long term dynamic simulations; however, the use of this model is restricted to the limited available data for model coefficients. The dynamic behaviour of the boiler is strongly influenced by the operation of the turbine, and there is a strong nonlinear cross coupling between boiler and turbine. The most significant time constant in this system is the boiler time constant, identified as Tb. The overall time constant is usually in the range about 180 to 360 seconds and tends to dominate the response of the dynamic boiler of turbine power output. Therefore, the smaller time constants are ignored as insignificant compared to Tb.

***d) Steam turbine model***

The various types of turbines are ranged from non-reheat, tandem compound single and double reheat, to cross compound single and double reheat. All compound steam turbine systems utilize governor-controlled valves at the inlet to the high pressure turbine control steam flow. The steam chest, inlet piping, re-heater and crossover introduce delays between valve movement and change in steam flow. The principle objective in modelling the steam system for stability studies is to account for these delays.

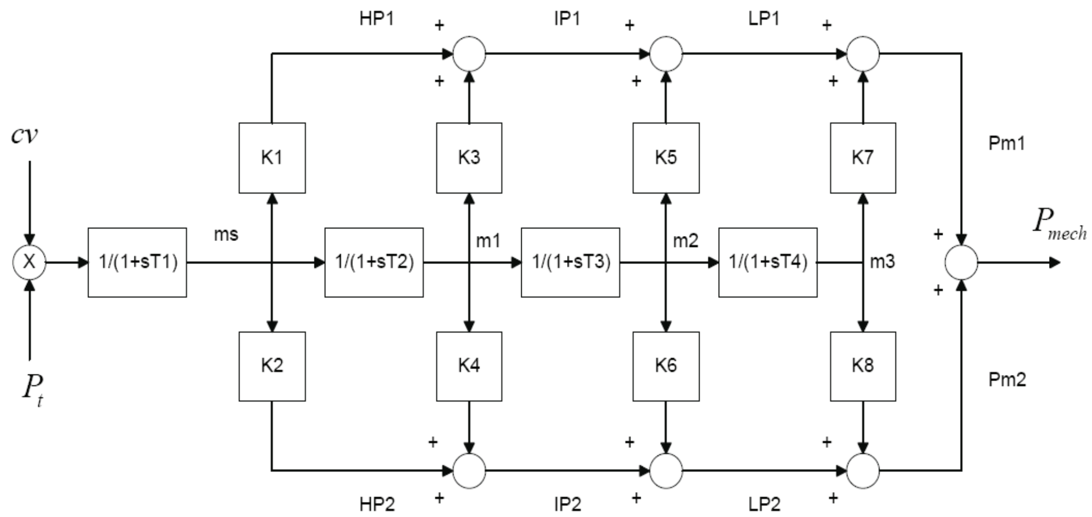


**Figure 4-5. Generic steam turbine model**

All compound steam turbine systems utilize governor-controlled valves (*cv*) at the inlet to the high pressure turbine control steam flow. The steam flow ($m_s$) is generated in the steam turbine model, as a function of turbine control valve *cv* and boiler main steam pressure ($P_t$) which are inputs for the steam turbine. The generic steam turbine model that would accommodate all types is shown in Figure 4-5 and detailed described in [23] and [24]. The principle objective in modelling the steam system for stability studies is to account for those delays of steam-chest, between valve movement and change in steam flow inlet introduced by piping, re-heater and crossover.

In this model, the time constants represent the charging of various volumes. The turbine response is modelled by the four time constants, the high pressure turbine bowl *T1*, the reheater *T2*, the crossover *T3*, and the time constant *T4*, is needed in the case of double reheat units. The model includes boiler pressure effects, but does not allow for control of intercept valves.

The parameters K1 to K8 determine the contributions from various turbines sections such as high pressure, intermediate pressure and low pressure turbines. These parameters represent the contributions to mechanical power of the various turbine sections as function of stage efficiency and enthalpy drop across the stage. The parameters of the generic steam turbine model are provided by DONG Energy [27], as shown in Table 4-5. The flow and power output equations can be written according to [28] as:

$$M_S = f(p_i, p_o, h_i, y) \tag{4-1}$$

$$P_m = M_S(h_i - h_o) \tag{4-2}$$

where $M_s$ is mass flow , $P_m$ is mechanical power, $p_i$, $p_o$ are up steam and down steam pressure respectively, $h_i$, $h_o$ are inlet and outlet enthalpy respectively , $y$ is valve stroke.

**TABLE 4-5**
**PARAMETERS OF STEAM TURBINE MODEL**

| Parameters | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 |
|---|---|---|---|---|---|---|---|---|
| Values (%) | 20 | 20 | 10 | 10 | 10 | 10 | 10 | 10 |

| Parameters | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Values (sec.) | 10 | 25 | 5 | 4 |

**e) Power plant operation mode** [23], [28]

The boiler control system is central in determining the overall behaviour of the generating units. The strategic behaviour of unit is governed by various boiler control configuration and the behaviour of the master control signal within these arrangement is now discussed.

**1. Sliding pressure mode**

Sliding pressure control mode has become popular because of its efficiency advantage. During this operation mode, the turbine valves are fixed in predefined optimum positions, which might be at valves wide open, or at a sequential valve point. Plant load is varied by ramping the steam supply pressure up and down using the boiler controls. If the turbine is wide open, frequency compensation can only be provided by the slow boiler control. If the optimum valve position is less than fully open, the turbine control is capable of responding to variations in grid frequency.

**2. Turbine following mode**

In turbine follow boiler control mode, rather than the boiler control is used to control the main steam pressure, the turbine valves are used as a relief valve to control pressure. The fast action of turbine control valve can accomplish almost perfect pressure control so that boiler pressure can be maintained constant. Under this operation mode, no use of the stored energy in the boiler is made. The MW output is varied not by directly manipulating the turbine valves, but by varying the boiler firing rate. Turbine following mode is preferred for thermal based load and nuclear plant, since it allows the generating unit to operate continuously at their maximum capacity rating.

**3. Boiler following mode**

In boiler following mode or constant pressure mode, change in generation are initiated by turbine control valves and the boiler controls respond with appropriate action upon change in steam and pressure. The turbine has access to the stored energy in the boiler and generation changes occur with a characteristic response of the turbine valves. Operating a generating unit in this mode does contain inefficiencies as throttling of the governor valves reduces the available steam flow, creating energy losses.

In this research project, as the centralised thermal power plants in the Danish power system are assumed to be operated with the sliding pressure control mode. Therefore, this operational mode is applied to the aggregated thermal power plant models for long-term dynamic simulation.

### 4.2.2 Model validation

In order to present the developed thermal power plant model for dynamic power system simulation during the loss of generations and loads, an aggregated model of a thermal power plant for long-term stability simulations is implemented and developed. This model is implemented in DIgSILENT PowerFactory. The aim of these studies is to analyze the aggregated model of a thermal power plant with regard to the secondary control, ramp rate limiter and the boiler dynamic. These simulation studies are provided to illustrate the developed model with regard to capability of unit's response and the secondary control in the thermal power plant.

The aggregated thermal power plant model for long-term dynamic simulation is demonstrated in three study cases. One is considering the capability of the unit's response with regard to the boiler dynamic. The next one is considering the units' response with regard to ramp rate limiter and thermal dynamic boiler. The aggregated models of thermal power plants with 400 MW rated power, with different ramp rate capabilities and unit time response is developed for this study. The comparison of the unit response between a power plant unit 1 and a power plant unit 2 with different ramp rate, but same boiler time constant in Table 4-6 is carried out.

Then, the comparison of the unit response between a power plant unit 1 and a power plant unit 2 with same ramp rate, but different boiler time constant in Table 4-7 is carried out. The influences of ramp rate limiter and dynamic boiler to the unit response can be observed. The last one is considering the AGC system with the secondary control of 4 aggregated thermal power plants with different ramp rate capabilities and boiler time constant which are operated with different participation factors *pf* as shown in Table 4-8.

**TABLE 4-6**
**RAMP RATE LIMITER AND BOLIER TIME CONSTANT OF THERMAL POWER PLANTS**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (second) |
|---|---|---|---|---|---|---|
| **Plant 1** | 400 | 1.5 | 2 | 4 | 2 | 150 |
| **Plant 2** | 400 | 2 | 2 | 8 | 2 | 150 |

**TABLE 4-7**
**RAMP RATE LIMITER AND BOLIER TIME CONSTANT OF THERMAL POWER PLANTS**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (second) |
|---|---|---|---|---|---|---|
| **Plant 1** | 400 | 2 | 2 | 4 | 2 | 150 |
| **Plant 2** | 400 | 2 | 2 | 4 | 2 | 300 |

**a) Unit step response of thermal power plant**

Figure 4-6 presents the unit step response of a thermal power plant 1 when a load step is introduced. The steam flow rate and active power generated from the power plant are demonstrated. At t = 900 s., a load step of 5% is introduced, resulting in a response from the thermal power plant. Figure 4-7 presents boiler pressure response in the simplified boiler model. The effect of the thermal dynamic boiler can be observed on the power plant, at a limit of the ramp rate of the generating unit. It can be observed that the unit's response is operated according to the unit time response in Table 4-6.

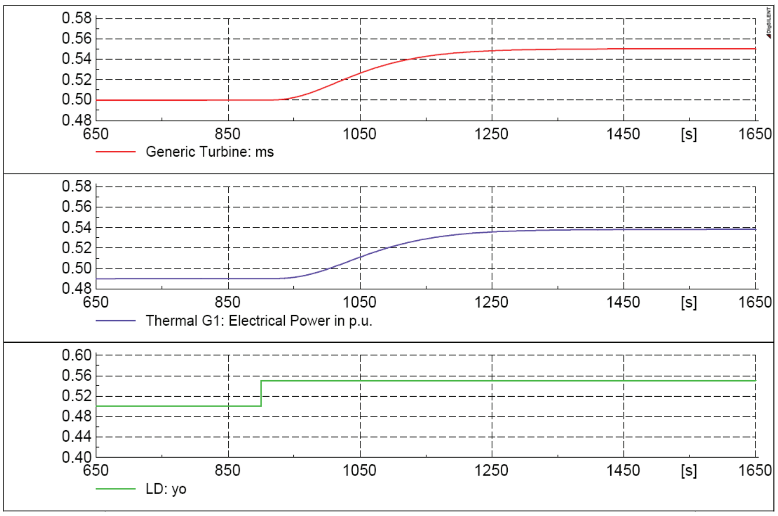


**Figure 4-6. Unit step response to a load step: power response and steam demand**

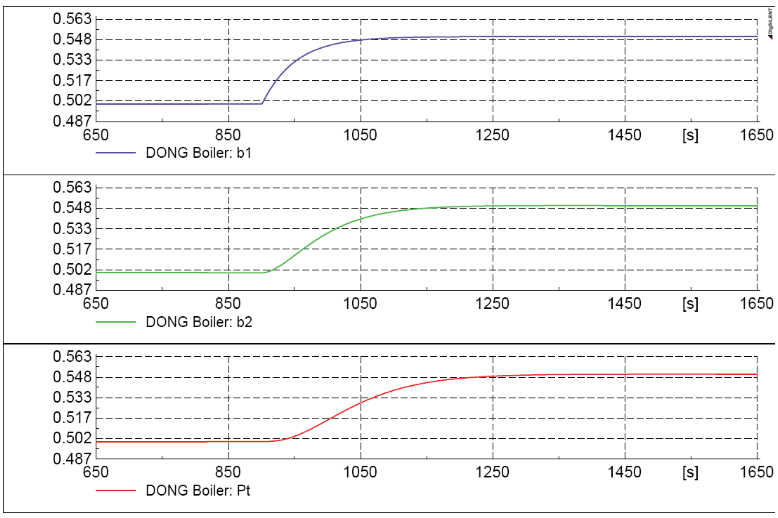


**Figure 4-7. Boiler pressure response to a step in power set point**

**b) Unit responses with regard to ramp rate limiter and thermal dynamic boiler**

The characteristics of various plants technologies can be represented by changing the ramping rate and the unit time response. Figure 4-8 present the responses from power plant 1 and power plant 2 with different ramp rate capability and the same boiler time constant of 150 seconds as shown in Table 4-6. At t = 900 s., a load step of 5% is introduced. The units' responses of two power plants with different ramp rate capability can be observed as shown in Figure 4-9. It has been found that the unit response for long term dynamic simulation is mainly determined by the ramp rate limiter component in the boiler turbine control model as mentioned in the earlier study in [25], while other components in the thermal power plant model are used for improving the real response of the power plant.

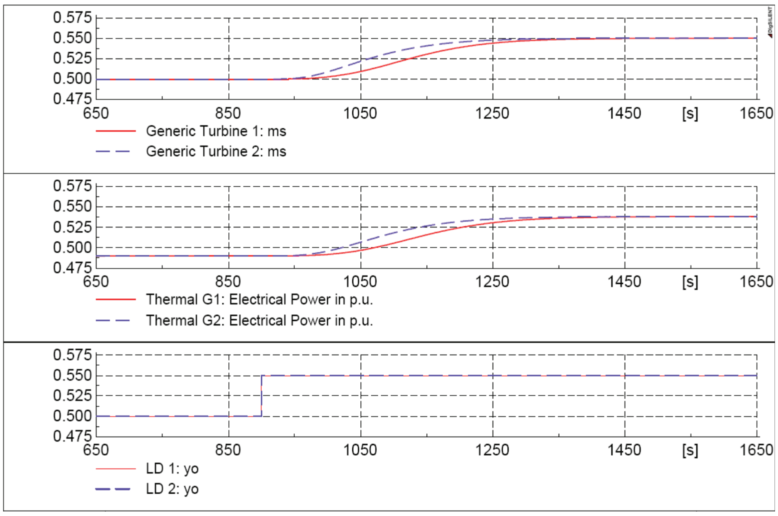


**Figure 4-8. Response of 2 power plants with different ramp rate**

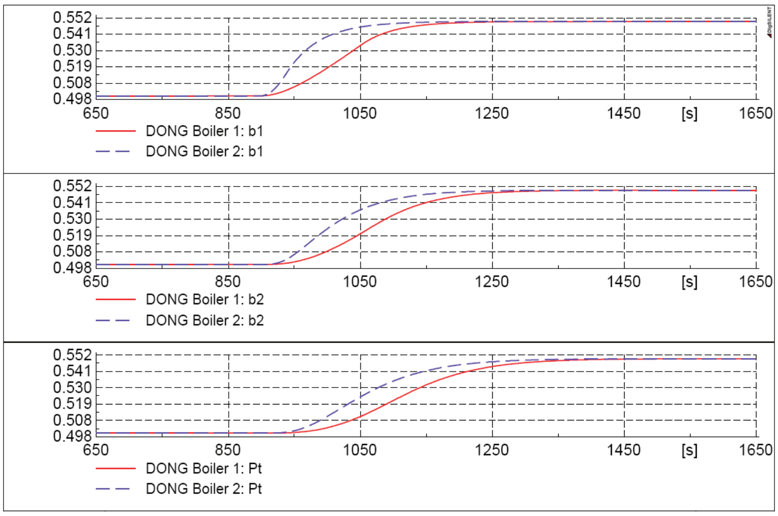


**Figure 4-9. Steam at an internal drum pressure in series with different ramp rate**

The simulation study of two power plants with the same ramp rate capability but with different units' time response as shown in Table 4-7, thermal power plant 1 with boiler time constant of 150 seconds and thermal power plant 2 with boiler time constant of 300 seconds, are illustrated in Figure 4-10. Steam flow at an internal drum pressure with different time constant in the thermal boiler can be observed as shown in Figure 4-11. It can be observed that the dynamic behaviour of the boiler is strongly influenced by the units' response.

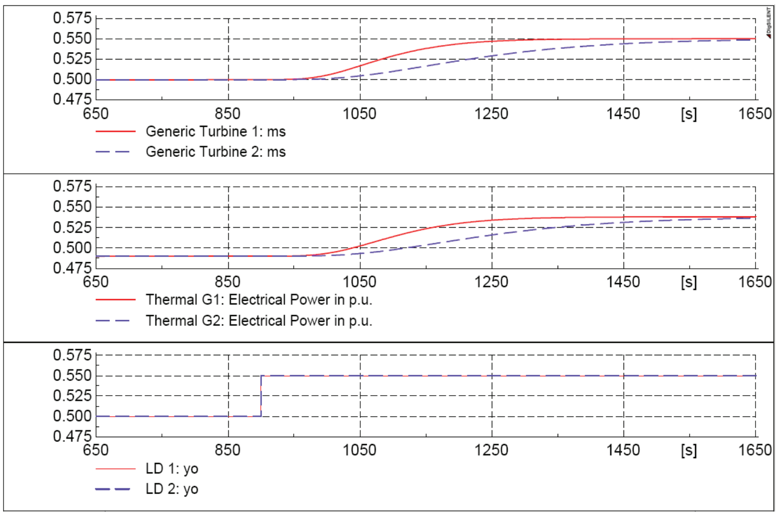


**Figure 4-10. Response of 2 power plants with different boiler time constant**

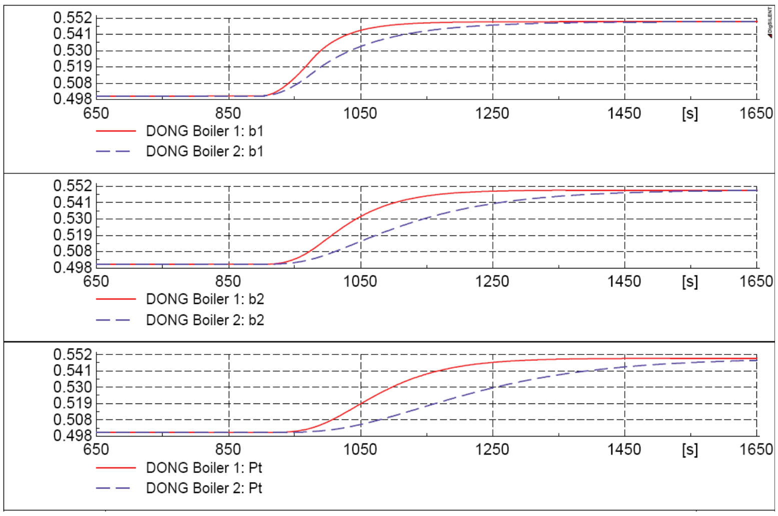


**Figure 4-11. Steam flow at an internal drum pressure in series with different boiler time constant**

**c) Long term dynamic simulation**

A dynamic simulation of the 4 thermal power plant models with different ramp rate limiters, units' time responses and are operated with different participation factors as shown in Table 4-8, together with given time series data of wind power generations, DCHP unit generations, loads, and power exchange with the Nordel system, on one week in 2003 is demonstrated. The AGC system computes unit set-points and sends set-point change commands to the selected units. The aggregated thermal power plant models applied in this analysis has been successfully validated against the measurement as shown in Figure 4-12. This analysis has shown the capability of the secondary control of the thermal power plants which nearly eliminate the power deviations with the UCTE system.

**TABLE 4-8**
**RAMP RATE LIMITER OF THERMAL POWER PLANTS IN ENDK-WEST**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (min) | Participation factor (pf) |
|---|---|---|---|---|---|---|---|
| **Plant 1** | 1738 | 2 | 2 | 4 | 2 | 3-4 | 0.55 |
| **Plant 2** | 700 | 1.5 | 2 | 4 | 2 | 3-4 | 0.1 |
| **Plant 3** | 392 | 2 | 2 | 8 | 2 | 3-4 | 0.25 |
| **Plant 4** | 625 | 2 | 2 | 4 | 2 | 5-6 | 0.1 |

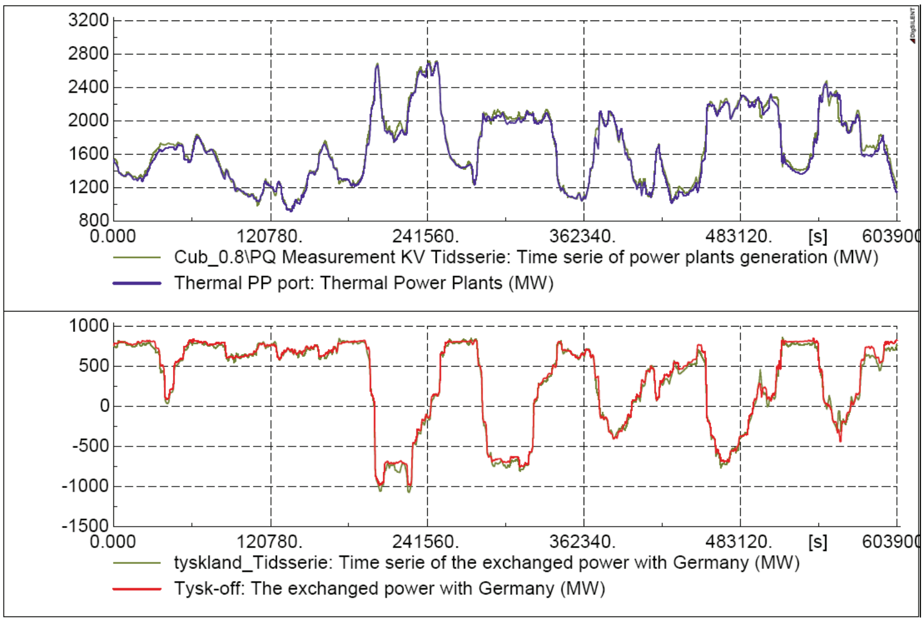


**Figure 4-12. Comparisons between the measured value (grey colour) and the simulation results of 1) power generation from thermal power plants (blue colour, above) and 2) power exchanged with Germany (red colour, below) on one week in 2003**

Figure 4-13 shows power production generated from the 4 aggregated thermal power plant models, operated with AGC system with different participation factors as shown in Table 4-8. In this simulation study, the different *pf* for 4 thermal power plants is given to illustrate the units' response with regard to different *pf* when operated with the developed AGC system. The unit responses of aggregated power plant models are investigated. It can be seen that the responses of plant 2 and plant 4 with *pf* = 0.1 is almost constant, while the responses of plant 1 with *pf* = 0.55 and plant 3 with *pf* = 0.25 give higher units' response.

From these simulation studies, the unit responses of the aggregated thermal power plant model are compared to measurements. From a comparison of the measurements and the simulations it is concluded that the models are reasonable accurate and can be used for presenting for power generating units in long-term dynamic simulation.

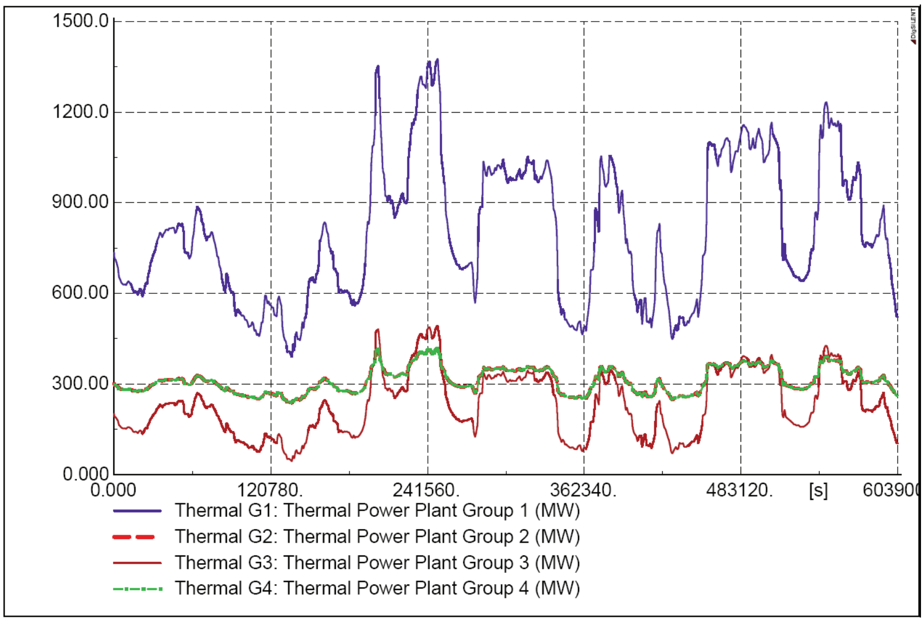


**Figure 4-13. Power production generated from 4 aggregated thermal power plant models, operated with AGC system with different participation factors as shown in Table 4-8**

# 4.3 Decentralized Combined Heat and Power (DCHP) unit model

From Table 2-1 and Table 2-2 in chapter 2, it can be seen that most of the decentralized power plants are based on gas turbine technology. Therefore, an aggregated model of a decentralized combined heat and power unit with gas turbine technology for long-term dynamic simulation is implemented and developed.

## 4.3.1 Aggregated DCHP unit model

An aggregated model of a DCHP unit with simple-cycle gas turbines, which is capable of the fastest response of all units in the systems, is developed based on the studies in [26], [29], [30]. An aggregated DCHP unit model consisting of a speed governor and a gas-turbine model with its power controller is illustrated in Figure 4-14. The unit response is mainly determined by a ramp rate limiter in the gas turbine model. DCHP units are integrated within the AGC system and can provide a fast secondary control for power balancing control.

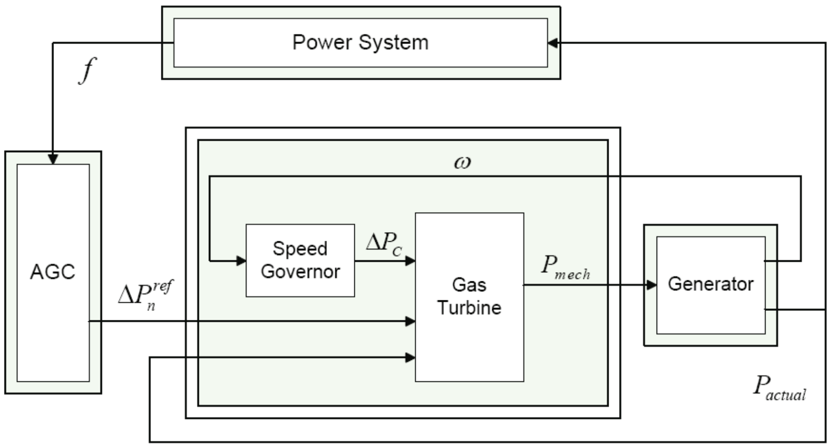


**Figure 4-14. An aggregated model of a DCHP unit**

The development of the model requires a compromise between making substantial simplification to reduce computation effort and maintaining the necessary adequacy to be able to predict the unit's influence on the system dynamic behaviour. The gas turbine model defines mechanical power ($P_{mech}$) as function of the power demand ($\Delta P_C$), the actual power generation ($P_{actual}$) and the power reference ($\Delta P_n^{ref}$) set by the AGC system. The speed governor model details the turbine control logic in response to change in generator speed ($\omega$). The parameters of the DCHP unit model are provided in the Appendix B.

**a) Speed governor model** [17], [26]

The control logic that governs the value of ($\Delta P_C$) is very specific to the type of the particular turbine, although the basic requirements are quite generic. The grid frequency has a major impact on plant behaviour, as it determines the generator speed and therefore the gas turbine speed. The general requirements cover speed regulation under normal load change duty (primary speed control). The turbine speed governor control model is developed as shown in Figure 4-15.

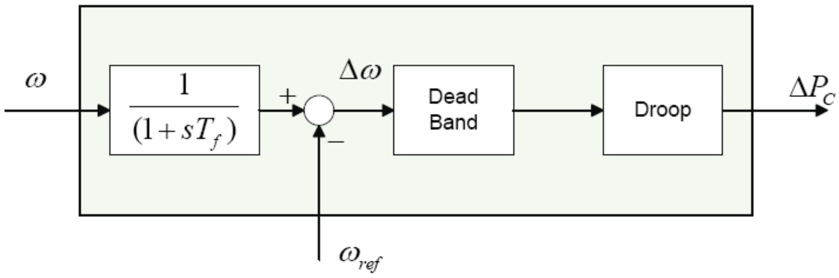


**Figure 4-15. Speed Governor of a DCHP unit**

This model consists of a pre-filter, a static dead band, and a droop ($1/K_D$). Any frequency excursions outside the specified dead band would generate a frequency error signal ($\Delta\omega$). The droop converts this frequency error signal into a power demand signal $\Delta P_C$ based on a droop characteristic. The power output of the gas turbine will increase or decrease according to $\Delta P_C$. This power demand signal is sent into the power limitation block in a gas turbine model as shown in Figure 4-16. However, the secondary control is the only concern in this project, the primary control in the governor model is omitted, and thereby $\Delta P_C$ is set to 0.0.

**b) Gas turbine model** [17], [26], [31]

The configuration of the gas turbine model consists of a power limitation block, a power distribution block and a gas turbine dynamics block as shown in Figure 4-16. The gas turbine model defines mechanical power $P_{mech}$ as function of a power demand signal $\Delta P_C$ and the power set point $P_{set}$ which is a function of actual power generation $P_{actual}$ and power reference $\Delta P_n^{ref}$ .

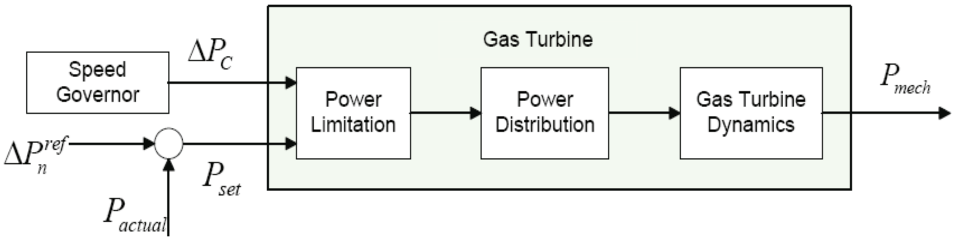


**Figure 4-16. Speed governor model and gas turbine model of a DCHP unit**

**1. Power limitation**

The power limitation model, as shown in Figure 4-17, provides the restriction limit on the gas turbine power response based on physical constraints of the combustion technology.

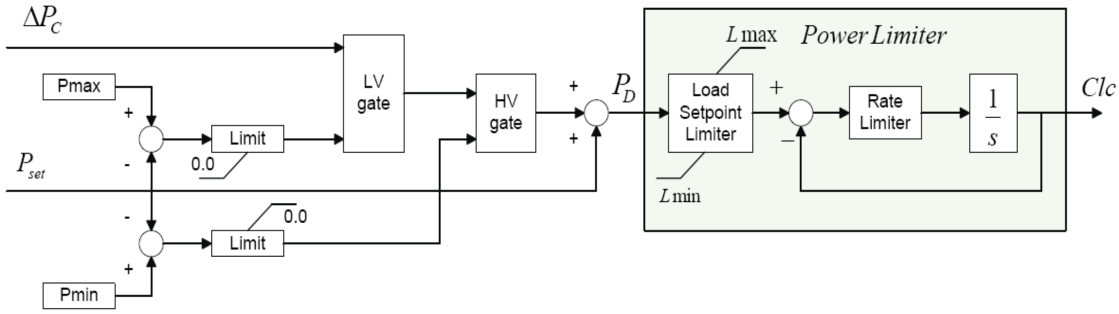


**Figure 4-17. Power limitation [26]**

The variables have the following meaning: LV is the low value gate, the lower value of the inputs will be selected to be an output of this block, HV is the high value gate, the higher value of the inputs will be selected to be an output of this block, $L_{max}$ is maximum load set point, $L_{min}$ is minimum load set point, $P_{max}$ is maximum power level for power generation control, $P_{min}$ is minimum power level for power generation control, *Rate Limiter* is load change rate limiter in p.u./sec.

The Power generation control of the gas turbine unit ($P_{set}$) is limited to a power output range between a maximum power level ($P_{max}$) and minimum power level ($P_{min}$). The power demand ($P_D$) is limited to a particular rate by the rate limiter block. The rate limiter prevents excessive over firing by controlling loading rate of the gas turbine unit. The command load change (*Clc*) is send to the power distribution block.

**2. Power distribution**

The commanded load change *Clc* signal is used to manipulate the fuel mass flow and the airflow. The air flow depends on the gas turbine shaft speed and the position of the variable inlet guide vane. The physical characteristics of fuel mass flow, air flow and allowable temperature, are represented in the control block by power contribution factors for the combustor units (*EV* and *SEV*) and compressor unit (*VGV*) as shown in Figure 4-18. In this project, the base load (*CFM*) as a function of frequency and temperature is set to 1.0 p.u.

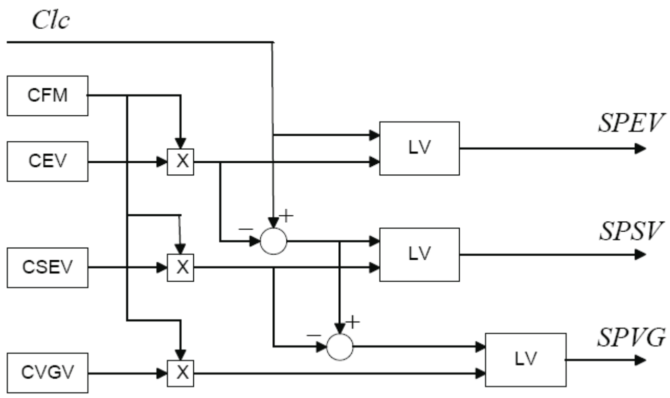


**Figure 4-18. Power distribution [26]**

The variables have the following meaning: *CFM* is base load function *f(frequency, ambient temperature)*, *CEV* is environmental burner capacity, *CSEV* is sequential environmental burner capacity, *CVGV* is variable inlet guide vane position compressor capacity. The power contribution factors (*SPEV*, *SPSV* and *SPVG*) are represented as function of the base load function with the combustor units *EV* and *SEV* and compressor unit *VGV* which are manipulated with the commanded load change *Clc* from power limitation block.

**3. Gas turbine dynamics** [26], [30]

The gas turbine dynamics is represented by the dynamics of the combustor and the compressor units in this model as shown in Figure 4-19. The dynamics of the combustors *EV* and *SEV* are represented by the first order lag functions. The dynamics of the compressor unit *VGV* is represented by the second order transfer function which can be written as:

$$\frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{4-3}$$

where $\omega$ is the un-damped natural frequency and $\zeta$ is the damping ratio of the compressor. Power limiter function consists of an upper and lower limit.

The power limiter block determines the mechanical power ($P_{mech}$) of the gas turbine in p.u. based on the gas turbine rated power, as function of dynamics of combustor units *EV* and *SEV* and compressor unit *VGV* with the power contribution factors *SPEV*, *SPSV* and *SPVG* from power distribution block.

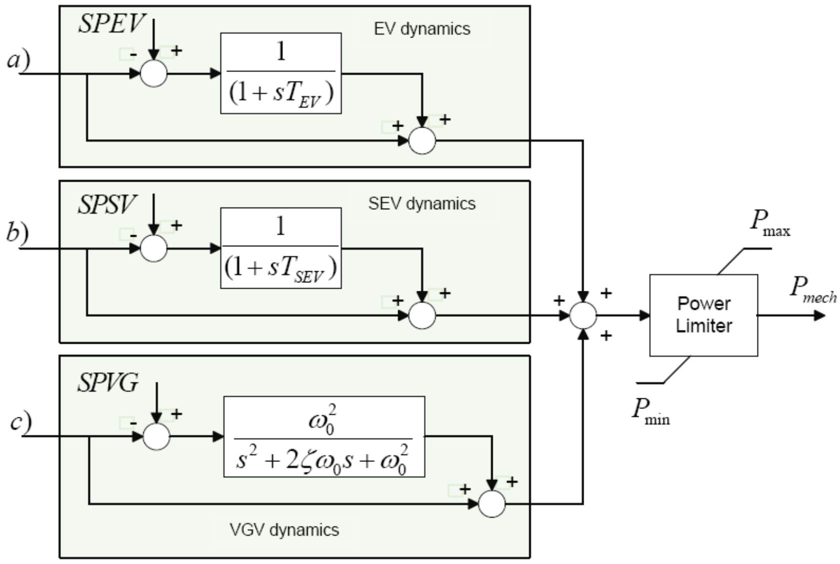


**Figure 4-19. Gas turbine dynamics [26]**

with

$$a): \min(CEV, P^{ref})$$
$$b): \max(0, \min(CSEV, P^{ref} - CEV))$$
$$c): \max(0, \min(CVGV, P^{ref} - CEV - CSEV))$$

The variables have the following meaning: *EV* is environmental burner, *SEV* is sequential environmental burner, *VGV* is variable inlet guide vane position compressor, $P_{max}$ is maximum power output, $P_{min}$ is minimum power output.

### 4.3.2 Model validation

The dynamic simulation of the developed DCHP unit model with the given time series data of the centralized thermal power plant generations, wind power generations, loads, and exchanged power with the Nordel system, on one day in 2003 is demonstrated. The aggregated DCHP unit model applied in this analysis has been successfully validated against the measurement as shown in Figure 4-20. As mentioned earlier in chapter 3 that the summation of the measurement is not equal to zero. The small power fluctuation generated from the DCHP model, seen in Figure 4-20 (above), is the result of perfection of the power control of the DCHP unit model, as it tried to compensate all power fluctuation from the planned power exchange with the UCTE system, seen in Figure 4-20 (below). Figure 4-21 shows the comparison between the measurement and simulation result of DCHP generations and the measurement and simulation result of power exchange with the UCTE system. The deviation of simulation from measurement of DCHP generation and the deviation of simulation from measurement of power exchange are shown in Figure 4-22

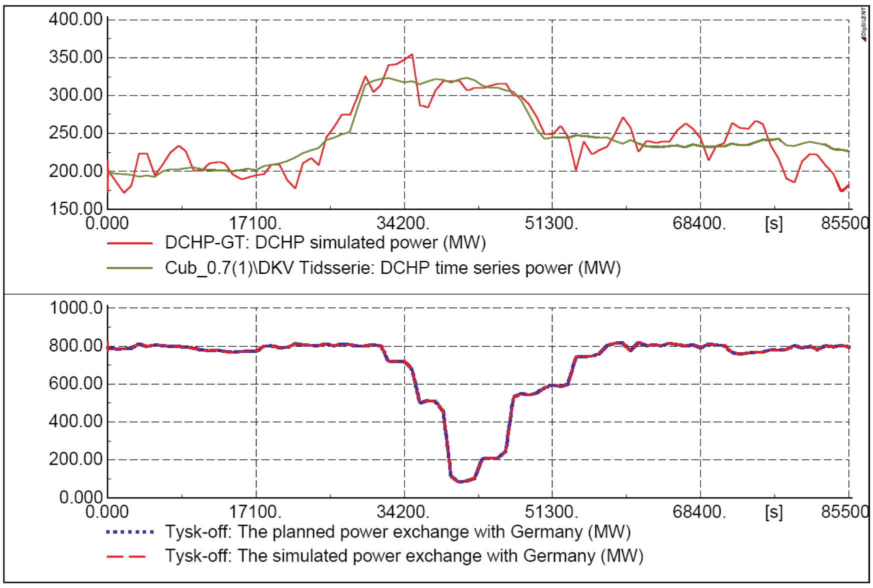


**Figure 4-20. Comparisons between the measurements and the simulation results of DCHP generation (above) and power exchange with Germany (below)**

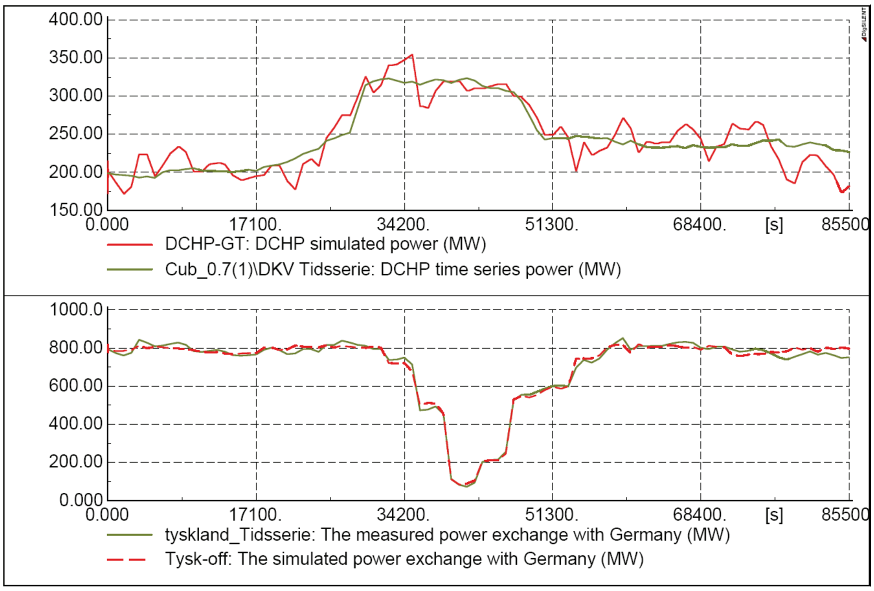


**Figure 4-21. Comparisons between the measurements and the simulation results of DCHP generation (above) and power exchange with Germany (below) on one day in 2003**

Figure 4-22 shows the comparison between the deviations of measurements from simulation results of DCHP generations and the deviations of measurements from planned power exchange with the UCTE system. It can be seen that the deviations of DCHP generations and of planned power exchange with the UCTE system are perfectly matched, as the DCHP model operated perfectly to compensate the power fluctuation.

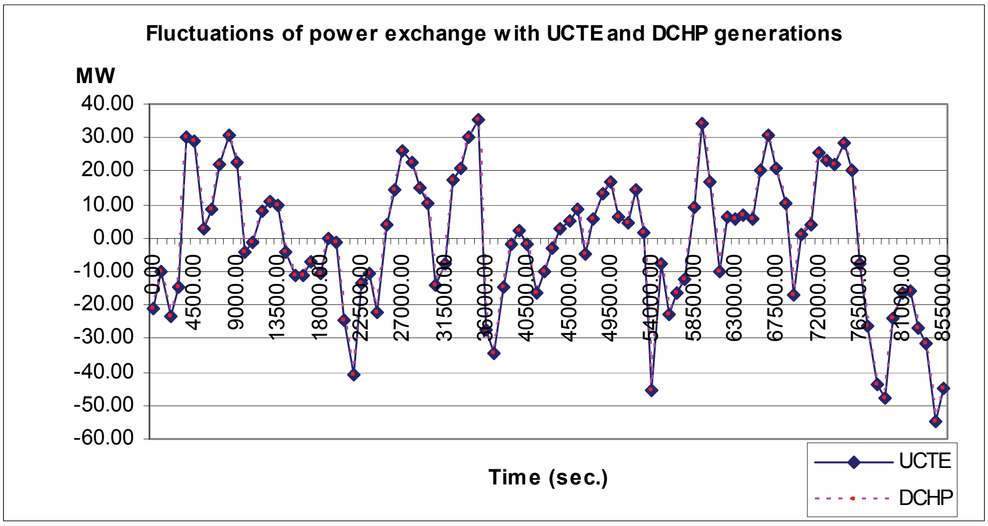


**Figure 4-22. Comparison between the deviations of measurements from simulation results of DCHP generations (red colour) and the deviations of measurements from planned power exchange with the UCTE system (blue colour) on one day in 2003**

## 4.4 On-land wind turbine model

The installed power capacity of wind power approached 3,120 MW in the Danish power system (January 2005) [3]. In the eastern Danish power system area, Energinet.dk-east, the installed power capacity of wind turbines was around 740 MW. The installed power capacity of wind turbines in the western Danish power system area, Energinet.dk-west, were around 2,380 MW.

In eastern Denmark, some increase in the wind power incorporated in on-land sites may come from the upgrading existing, small wind turbines to newer and larger ones, and also from the use of new sites on the islands of Lolland and Falster characterized by good wind conditions [8].

In western Denmark, an increase in the wind power incorporated in on-land sites may occur by upgrading or replacement of existing (small) wind turbines with ratings below 1MW (up to 900 units with total 175MW) by new, more efficient wind turbines with ratings of several MW (between 150 and 200 units). This upgrading may give up to 350MW more on-land wind power in the whole country. However, the major upgrading is expected in Jutland, the continental part of the western Denmark [8].

The majority of on-land wind turbines in the Danish power system are fixed speed, active-stall wind turbine equipped with squirrel-cage induction generators. A small correlation between the total output powers of the different wind turbines, which may eliminate some of the power fluctuations, last from ten minutes to one hour, can be seen from the grid [2]. In this project, on-land wind turbines are modelled as a negative load. Time series data of the on-land wind power production is used as an input to the negative load model. The wind power measurements are with 15 minutes time intervals. The simplified model of on-land wind turbines is developed as shown in the Figure 4-23.

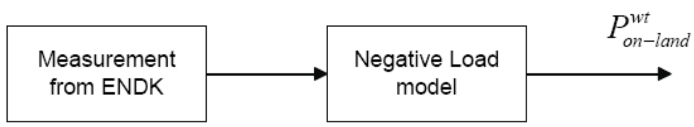


**Figure 4-23. A simplified model of on-land wind turbines (ENDK: Energinet.dk)**

# 4.5 Wind farm model

In Danish power systems where a significant part of the power generation comes from wind power, power balancing control is one of the most important issues with regard to the power system stability. An aggregated wind farm model with wind farm power control is needed to investigate the dynamic characteristic of wind power generation that can affect the power system performance during and following a disturbance due to wind power fluctuation.

In this chapter, an aggregated wind farm model for long-term dynamic simulation is developed. A model is implemented and developed as a generic model for both fixed speed wind farms and variable speed wind farms. Control strategies in the wind farms with regard to power balancing control for both normal conditions and during fluctuating power productions from wind farms are included in the model. The wind farm model presented here is basically an equivalent transfer function of first order which has the wind speed as input and the active power as output. The model structure is not directly related to a certain wind turbine and generator technology. However, the model parameters and time constants of the various model blocks are wind turbine technology dependent.

The model is intended for estimating the amount of wind power that can be absorbed in the power system taking into account the inherent characteristics of wind power and an accepted level of power system long-term stability, rather than to make accurate predictions of the impact of a specific wind farm with given wind turbine types. The ability of a wind farm to participate in control tasks represents a number of services that the power system operator requires from power generating unit. This is included in the wind farm power control model. For a simulation model representing an entire wind farm, it has to deal with time constant in several seconds up to minutes. The response of a wind farm can at times be an important variable, affecting the dynamic performance of the power system operation. For a power system impact study, when the impact of an entire wind farm to a power system is studied, a detailed model of every individual wind turbine would require too much calculation time [32]. An aggregated wind farm model is developed by one equivalent model representing the entire wind farm seen from the point of common coupling.

When a large scale system is viewed as one system rather than a group of interconnected subsystems, the fast components of the large scale system become negligible compared to the slow components when a large time constant is considered. The development of an aggregated wind farm model for long-term dynamic simulation is presented. The model is developed to be used together with the AGC system, so it has to deal with time constants in several seconds up to minutes. This model can be used to estimate the general power response, taking into account the specific and unavoidable characteristic of wind power fluctuations. The models are based on simplifications of wind farm controls with regard to the dynamics of the power gradient control and the effect of various modes of the overall wind farm power control system.

### 4.5.1 Aggregated wind farm model

The development of the model requires a compromise between making substantial simplification to reduce computation effort and at the same time maintaining the necessary adequacy to be able to predict the unit's influence on the system dynamic behaviour. An aggregated wind farm model is implemented as shown in Figure 4-24. The generic model is used for long-term dynamic simulations considering the wind farm power control system with the power gradient control.

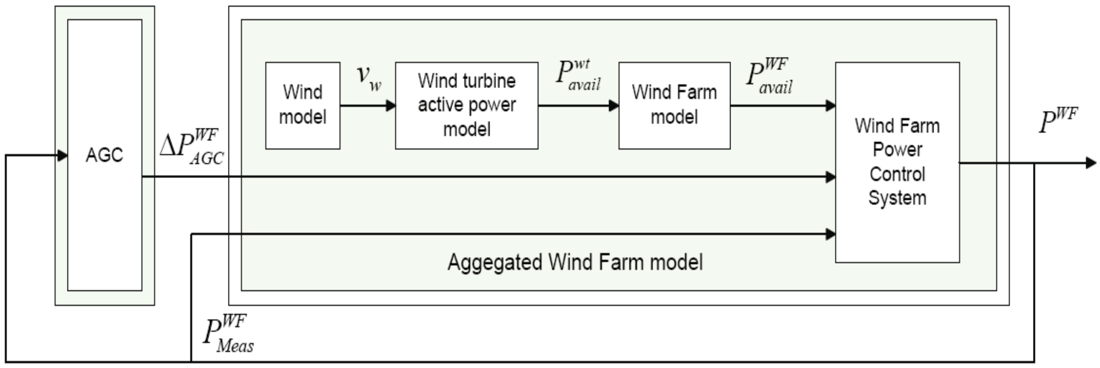


**Figure 4-24. Block diagram of an aggregated wind farm model**

The variable have the following meaning: $v_w$ is wind speed, $P^{wt}_{avail}$ is wind turbine available power, $P^{WF}_{avail}$ is wind farm available power, $P^{WF}_{Meas}$ is wind farm measured power at PCC, $P^{WF}_{demand}$ is wind farm demand power, and $\Delta P^{WF}_{AGC}$ is power set point from AGC system.

The aggregated wind farm model consists of a wind speed model, a wind turbine active power model, a wind farm model, and a wind farm power control system model. In the wind farm power control system, the balance control, delta control and power gradient control as explained in [9] are included. The wind turbine active power block defines $P^{wt}_{avail}$ as function of $v_w$. The wind farm block deliver the wind farm available power ($P^{WF}_{avail}$) as function of $P^{wt}_{avail}$. The wind farm power control system develops $P^{WF}$ in response to $P^{WF}_{avail}$, $P^{WF}_{Meas}$ and $\Delta P^{WF}_{AGC}$ set by the AGC system.

#### 4.5.1.1 Wind model

As the wind speed difference between different wind turbines in the wind farm is assumed to be small, one equivalent wind speed model can be used. In the wind farm, it is also assumed that the hub height is the same for all the turbines, which is the case in the large offshore wind farms. In this project, a wind speed model is developed as a wind speed time series.

#### 4.5.1.2 Active power model

The wind turbine power curve as shown in Figure 4-25 has an upper limit for the output power, which is equal to the rated power of 2 MW, being 1 p.u. In Figure 4-26, the wind speed is low-pass filtered and converted into active power using the wind turbine power curve. The time constant of the low-pass filter corresponds to the average wind speed fluctuation for all wind turbines in a wind farm. This time constant depends on the average wind speed, but is assumed constant for this simplified model. The characteristic of wind speed fluctuations at rated power operation is taken into account by the first order transfer function. The active power model is used to represent different wind turbine technologies by means of appropriate selection of wind turbine power curve [32].

The wind speed time series is used as an input to the first order filter in the active power model. The wind speed is low-pass filtered into an equivalent wind speed and used as an input for the active power model. The variables have the following meaning: $v_w$ is wind speed time series, $P^{WF}$ is wind farm power, $v_{eq}$ is average equivalent wind speed.

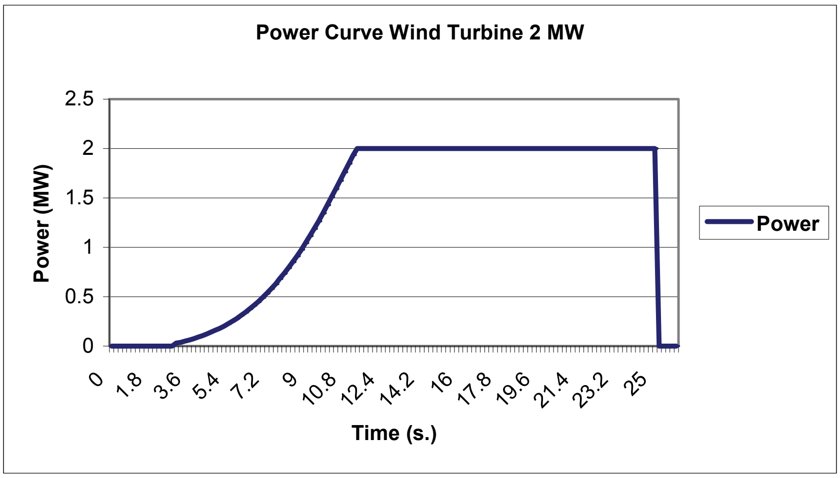


**Figure 4-25. Power curve of a wind turbine, with 2 MW rated power [33]**

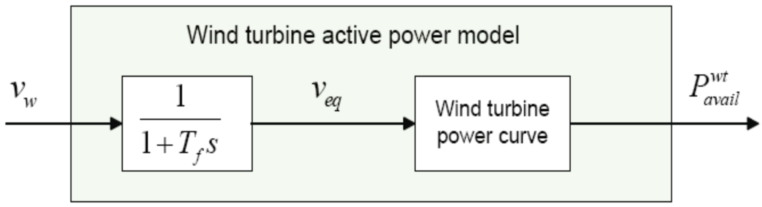


**Figure 4-26. Equivalent transfer function for active power model**

### 4.5.1.3 Wind farm power control system [36], [37], [38], [39]

With the wind farm power control system, the wind farm can be used to provide the regulating power contributing to the power balance control. A power control system of an aggregated wind farm model for long-term power system dynamic simulation is developed as shown in Figure 4-27 and Figure 4-28. In this model, the total wind farm power control consists of the control set by the power operation mode and the wind farm power controller. Power operation mode deliver a power demand signal to the wind farm power controller in response to the power demand set by the operator or the AGC system. The wind farm power controller defines a power reference signal as function of the power demand, the wind farm available power and the measured power. The aggregated wind farm develops the actual power production in response to change in the power reference signal from the wind farm power control system.

In assessing the ability of a power controller to support power control and modelling its dynamic performance, it is important to recognize that the validity of these assumptions should be questioned. The actual performance will depend on many factors such as the type of wind turbine, and the characteristic of the blade pitch controls which will affect the power control dynamic performance in response to the power balancing control. A power gradient response over a period of several seconds to minutes can be significant to system behaviour following a disturbance resulting in significant imbalance between generations and loads.

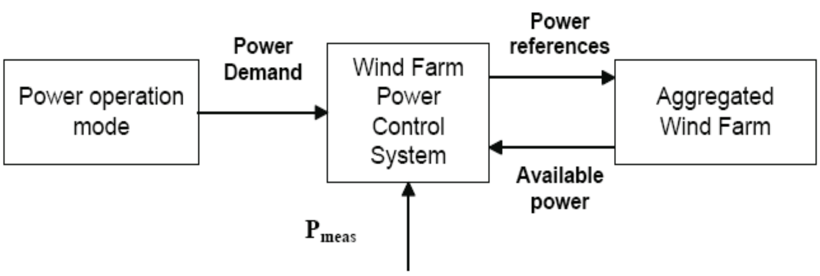


**Figure 4-27. Wind farm power control system**

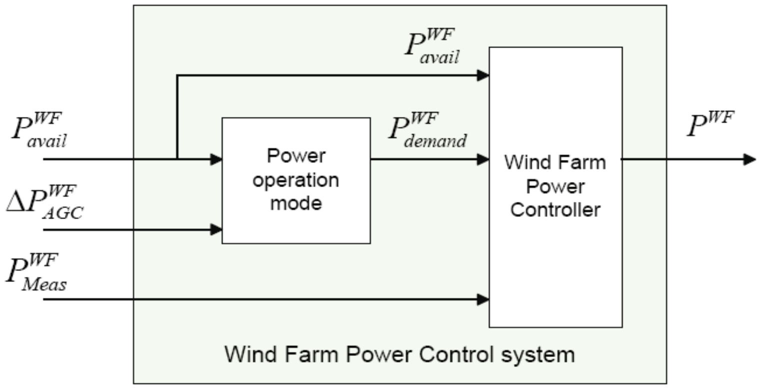


**Figure 4-28. Wind farm power control system model**

The wind farm power controller defines wind farm power reference ( $P^{WF}$ ) as function of $P_{Meas}^{WF}$ , $P_{avail}^{WF}$ and $P_{demand}^{WF}$ signals. The power operation mode deliver the power demand signal ( $P_{demand}^{WF}$ ) to the wind farm power controller in response to $P_{avail}^{WF}$ and $\Delta P_{AGC}^{WF}$ .

## 4.5.2 Wind farm power control

The behaviour of a wind farm seen from the grid side is based on the requirements of the Danish TSO for wind farms and wind turbines. The main attention on these requirements is drawn to the power control of large wind farms. The Grid Code Requirement (GCR) deals with the technical requirements to the wind farm with regard to power and frequency control. According to the GCR the wind farm must be able to participate in control tasks on an equal level with conventional power plants, constrained only by the limitations imposed at any time by the existing wind conditions [9].

Active power and power regulation for wind farm control functions at voltages above 100 kV [9] can be summarised as follows:

1. Absolute production constraint
2. Delta production constraint
3. Balance regulation
4. Stop regulation
5. Power gradient constraint
6. System protection
7. Frequency control

This project focuses on active power balance control in long term system stability. Therefore, only the Delta production constraint, the Balance regulation and the Power gradient constraint are included in the wind farm power control system. The absolute production constraint is not included in the wind farm power control model. As the absolute production constraint is operated in the same function as the balance control. Stop regulation, system protection and frequency control are not included in the model, as they are not the issue in this project.

The active power control functions included in the aggregated wind farm model are as follows:

1.) *Balance control*:

The wind farm production can be adjusted downwards or upwards in steps at constant levels. During periods with reduced transmission capacity in the grid, wind farm must be able to operate at reduced power levels with all turbines running. The production (measured as a 1-min average value) of the wind farm must not exceed the power set point with more than 5% of the rated power of the wind farm.

2.) *Delta control*:

The wind farm must be able to participate in the area balance control (the secondary control). In this operation mode the power set point will be generated by the transmission system control and sent to the wind farm through the SCADA-system (Supervisory Control And Data Acquisition system). The updating interval to the wind turbines will be in the order of 1 s.

3.) *Power gradient control*:

Large variations in the power production can be generated from wind farm by fluctuating wind speed. The wind farm must be able to impose a positive rate of power change limitation in such situations. This control can not limit the negative power gradient. The rated power set point can be set through the SCADA-system to the wind farm main controller. The updating interval to the wind turbines will be approximately in the order of 1 s.

A wind farm power control system with balance control, delta control and power gradient control is illustrated in Figure 4-29.

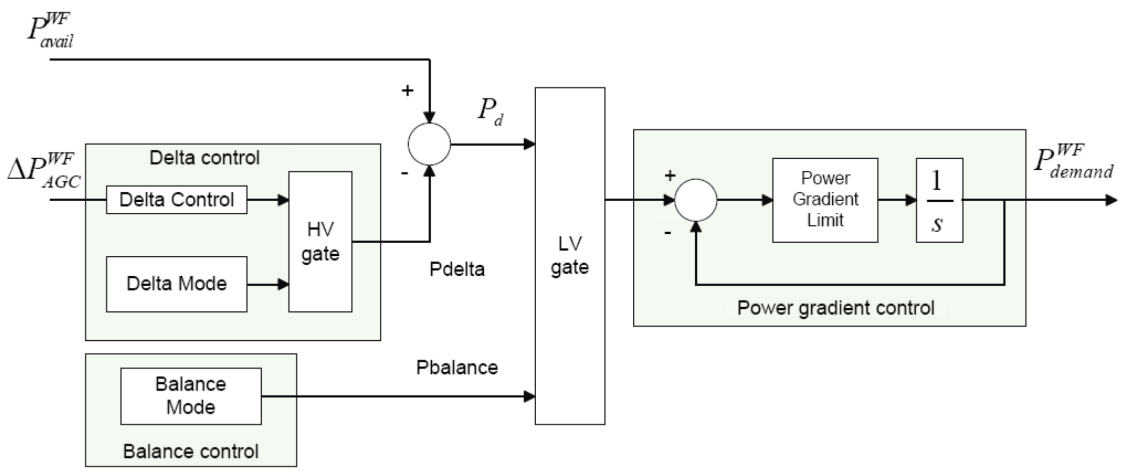


**Figure 4-29. Wind farm power control with balance control, delta control and power gradient control**

The power High Value (HV) gate block develops the delta power as function of power demand ( $P_{AGC}^{WF}$ ) set by the AGC system and planned delta power ( $P_{delta}^{Plan}$ ) set by the system operator. The power Low Value (LV) gate block develops the demand power $P_{demand}$ input to the power gradient control in response to power demand ( $P_d$ ) and balance power ( $P_{balance}$ ) set by the system operator. The power gradient block defines $P_{demand}^{WF}$ in response to $P_{demand}$ .

$$P_{delta} = \max(\Delta P_{AGC}^{WF}, Delta) \tag{4-4}$$

$$P_d = P_{avail}^{WF} - P_{delta} \tag{4-5}$$

$$P_{demand} = \min(P_d, P_{balance}) \tag{4-6}$$

A wind farm power control system with balance control, delta control and power gradient control is illustrated in Figure 4-30.

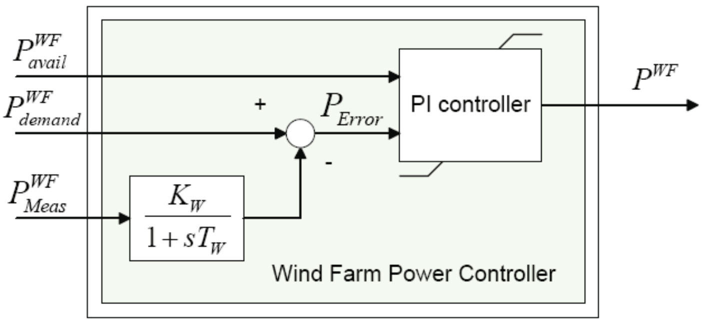


**Figure 4-30. Wind farm power controller**

The power High Value (HV) gate block develops the delta power as function of power demand ( $P_{AGC}^{WF}$ ) set by the AGC system and planned delta power ( $P_{delta}^{Plan}$ ) set by the system operator. The power Low Value (LV) gate block develops the demand power $P_{demand}$ input to the power gradient control in response to power demand ( $P_d$ ) and balance power ( $P_{balance}$ ) set by the system operator. The power gradient block defines $P_{demand}^{WF}$ in response to $P_{demand}$ .

### 4.5.3 Model validation

In order to present the proposed wind farm model for dynamic power system simulation during the wind speed fluctuation. An aggregated wind farm model with wind farm power control system for long-term dynamic simulations is implemented and developed. The aim of the case study is to validate the developed aggregated wind farm model with wind farm power control system. The capabilities of wind farm power control system have been simulated in two study cases. One is the validation of the transfer function wind turbine model; the output of the equivalent transfer function is compared with the output of the detailed wind turbine model with variable wind speed. The other is considering balance control, delta control, and power gradient control of the wind farm power control system.

The detailed DFIG wind turbine model, which is developed by Risoe National Laboratory [40], as illustrated in Figure 4-31 is shortly described here. The wind turbine model consists of wind speed model, aerodynamic model, mechanical part and electrical part models and control system. It provides an equivalent wind speed $v_{eq}$ to the aerodynamic model. The aerodynamic model is based on table with the aerodynamic power efficiency Cp (θ, λ), which depend on the pitch angle θ and the tip speed ratio λ. The aerodynamic model uses an equivalent wind speed $v_{eq}$, the wind turbine rotor speed $\omega_{WTR}$ and the blade pitch angle $\theta_{pitch}$ as inputs. Its output is the aerodynamic torque $T_{aero}$. $v_{eq}$ is a single wind speed time series, which represents the whole field of wind speeds in the rotor plane of the wind turbine. The mechanical model interfaces to the electric model as described above, and to the aerodynamic model. The inputs to the mechanical model are the aerodynamic torque $T_{aero}$ and the generator speed $\omega_g$. The outputs are the wind turbine rotor speed $\omega_{WTR}$ and the generator mechanical power $P_t$. The electric model interfaces with the power system by the active power $P$ on the wind turbine terminals. The electric model outputs the active power $P_{MS}$ at the main switch, representing the measured voltages and currents of the control system. The generator is driven by the mechanical power from the mechanical model. The control system consists of pitch control and frequency converter provides a number of control signals for the wind turbine. The detailed study of a detailed wind turbine model can be found in [40].

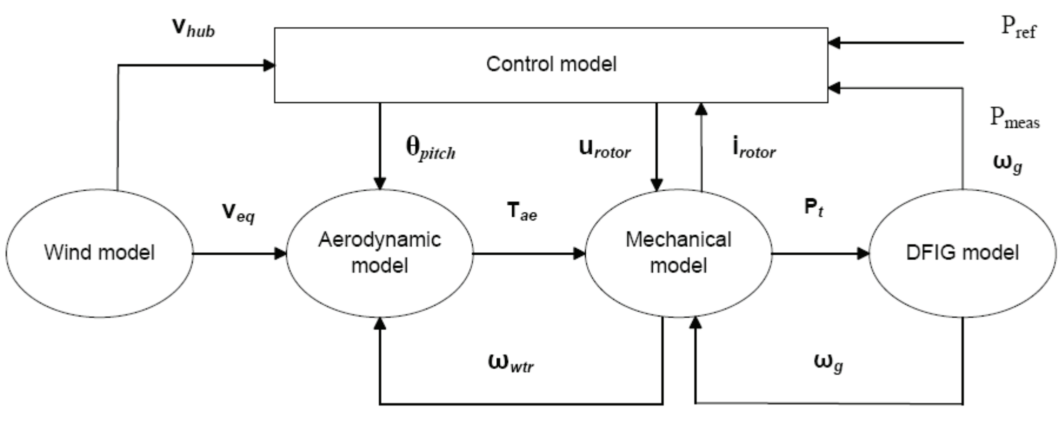


**Figure 4-31. A detailed DFIG wind turbine model**

#### 4.5.3.1 Validation of a transfer function wind turbine

The simulation result of the equivalent transfer function (ETF) wind turbine level in an aggregated wind farm model is compared with the simulation result of the detailed model for the wind speed variation from 6 m./s. to 20 m./s. as shown in Figure 4-32. The comparison of power output with the decreased wind speed from 20 m./s. to 6 m./s. is shown in Figure 4-33.

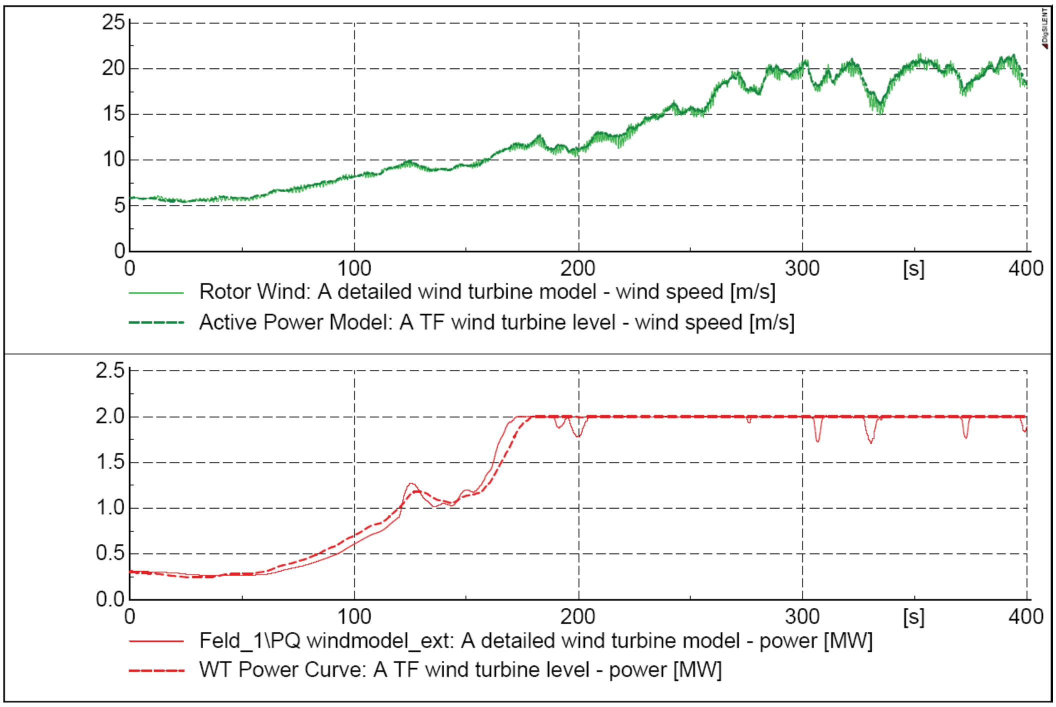


**Figure 4-32. Comparison between a wind turbine level in an ETF wind farm model and a detailed wind turbine model: wind speed 6 m/s to 20 m/s**

The simulations of the detailed model and the ETF model with the wind speed variation from 6 m./s. to 20 m./s., as shown in Figure 4-32 show a very good correspondence.

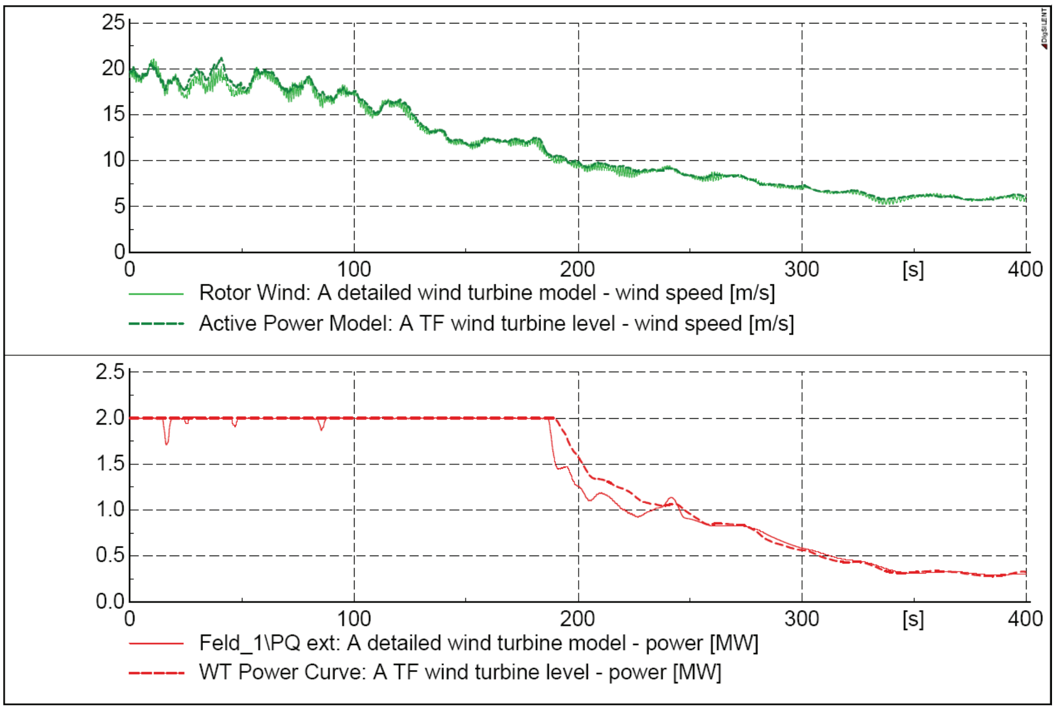


**Figure 4-33. Comparison between a wind turbine level in an ETF wind farm model and a detailed wind turbine model: wind speed 20 m/s to 6 m/s**

The simulations of the detailed model and the ETF model with the wind speed variation from 20 m./s. to 6 m./s., as shown in Figure 4-33, show also a very good correspondence.

The simulations of the aggregated wind turbine model are compared with that of detailed model. The agreement between the responses of the aggregated and detailed models is rather close. For long-term dynamic simulations, the accuracy achieved from aggregated models will in most cases be sufficient.

### 4.5.3.2 Wind farm power control system

Figure 4-34 and Figure 4-35 present simulation results of the power control in the aggregated wind farm model using the balance control mode. In the beginning the wind farm performs normal operation and has to produce maximum power. The power demand from the operator is stepped down to 120 MW and then stepped up to the maximum production. In the power balance control mode the wind farm power control show a good performance when the active power demands from the grid operator is stepped down and up to the different set points, taking into account a power gradient control of 5 MW/min.

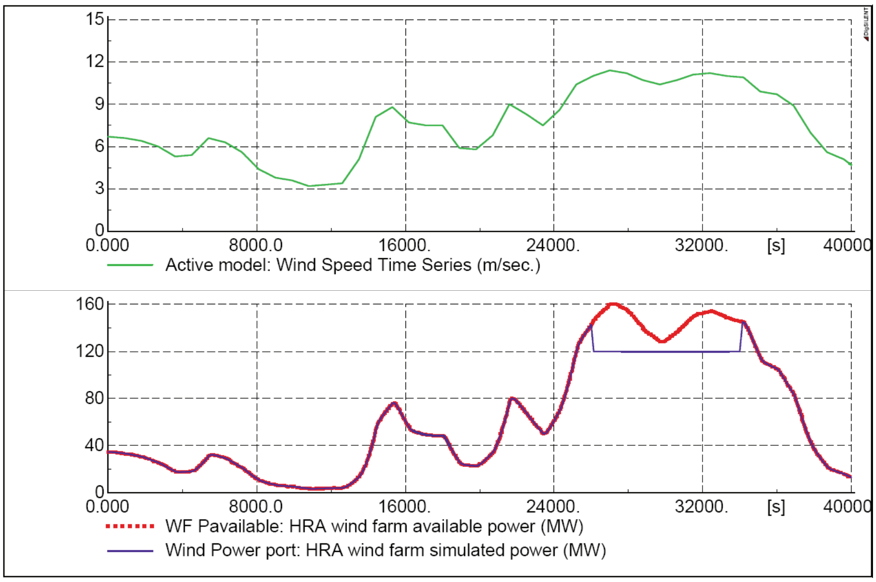


**Figure 4-34. Wind farm power control: balance control 120 MW**

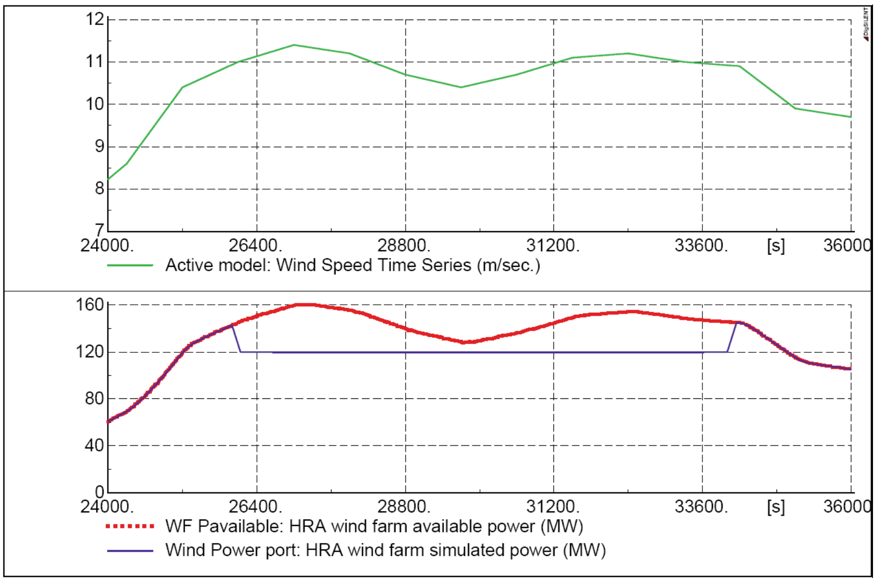


**Figure 4-35. Detailed view of the balance control 120 MW**

Figure 4-36 and Figure 4-37 present simulation results of the power control in the wind farm model using the delta control mode. In the beginning the wind farm performs normal operation and has to produce maximum power. The delta production constraint is changed to 30 MW and then changed to no production constraint. In the power delta control mode the wind farm power production follows the wind farm power reference, taking into account the power ramp rate limiter. The simulation results show a good performance of the power control system. The adjustment upward and downward of the wind farm power production is performed with power gradient control of 5 MW/min.

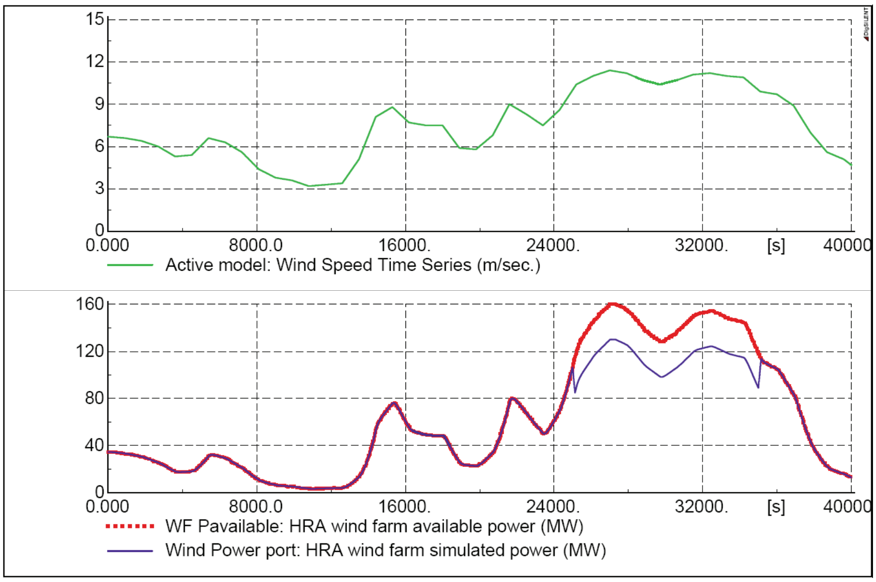


**Figure 4-36. Wind farm power control: delta control 30 MW**

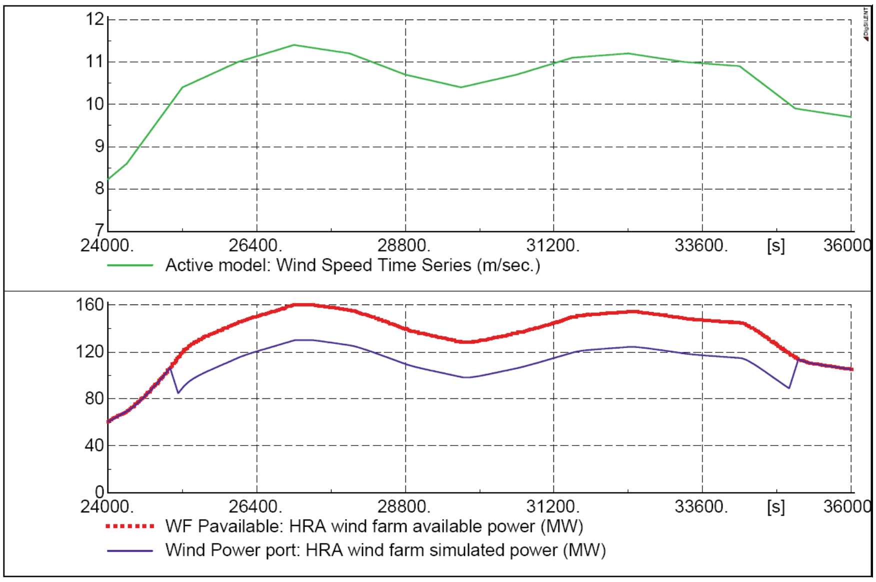


**Figure 4-37. Detailed view of the delta control 30 MW**

# 4.6 Summary

In this chapter, aggregated models of the power generating units in the Danish power system are presented. The use of aggregated models reduces the modelling effort and the amount of parameters. It also eliminates the necessity to specify unnecessary data for each generating unit in the system. The aggregated models are particularly developed for use in power system long-term dynamic simulation and contain all subsystems and time constant that are of importance in the simulation.

An aggregated model the centralized thermal power plant for AGC purpose is implemented and developed. This model is intended for estimating the degree of the secondary control that can be supported in a given grid point, rather than to make accurate predictions of the impact of a specific unit with a given technology. It can be used to estimate the general units' response at a certain grid point, taking into account the specific and unavoidable characteristic of the thermal boiler dynamic. The regulating power control of a thermal power plant with ramp rate capabilities and unit time response is presented. It can be found that the model is put under the pressure/flow effects only. It has been also found that the unit response for long-term dynamic simulation is mainly determined by the ramp rate limiter component in the boiler turbine control model together with the dynamic behaviour of the thermal boiler, while other components in the model are used for improving the real response of the power plant.

An aggregated model the DCHP unit for AGC purpose is also developed. It can be used to estimate the unit response on a certain grid point, taking into account the specific and unavoidable characteristic of DCHP plant. The regulating power control of DCHP unit with ramp rates capabilities is presented. It can be observed that the fast unit response is mainly determined by the ramp rate limiter. An aggregated model of DCHP units is integrated within the AGC system and can provide the fast secondary control.

A simplified model of on-land wind turbines and an aggregated offshore wind farm model with wind farm power control system are also presented. It is the purpose of this chapter to detail the model structures that apply to the equivalent transfer function and several power control modes. Results from simulation studies are used to investigate the capability of the aggregated wind farm model including wind farm power control system and the units' response which is mainly determined by the power gradient control. This simulation study shows that the transfer function model can be used in an aggregated wind farm model when dealing with simulation studies covering a long time frame. The regulating power control of a wind farm with power control capabilities is presented.

The simulation results show a good performance of the power control system. The adjustment upward and downward of the wind farm power production is performed with a power gradient control of MW per min. It can be observed that the most relevant dynamic of the units' response is due to the power gradient control and the time constant in active power control block. The developed wind farm model is suited to simulate the impact of wind speed fluctuations on the power system, and the grid support capabilities of a wind farm in normal operation and during grid disturbances.

The unit responses of the aggregated power generating unit models are compared with measurements. The agreement between the responses of the aggregated model and the measurement is close. For long-term dynamic simulations, the accuracy achieved from the aggregated models will in all cases be sufficient.

# Chapter 5

# Modelling of System Interconnections

## 5.1 Introduction

Chapter 5 introduced models of the most important contemporary system interconnections concept that play an important role in the power balancing control of the Danish power system operation. The Danish power system has system interconnections with its neighbouring countries, Norway and Sweden (Nordel system), and Germany (UCTE system) as already mentioned in Chapter 3. The Great Belt Link HVDC connection will make it possible to utilize the regulating power control incorporated in the eastern Denmark to work together with that established in the western Denmark.

This chapter continues the development of the models for representing the system interconnections for the power system dynamic simulation. First, the concept of the system interconnections with the UCTE area and the Nordel system and their control strategies are defined. Simplified models of the interconnections with the Nordel system are presented. The limitation of the power exchange between the Danish power system and the Nordel system due to the new settlement model of the power transaction is described. The system interconnections between the Danish power system and the UCTE system are also presented. The power balancing control issue at the Danish – German border is described and the balancing control strategy is demonstrated.

In the second part of this chapter, the GBL HVDC connection between the eastern and the western Danish systems is presented. The technical specification of the GBL HVDC connection is described. The developed model of the GBL connection and its regulating power control between the eastern and the western Denmark are presented. The capability of the GBL connection on the power balancing control of the Danish power system is illustrated.

# 5.2 Interconnections with Nordel and UCTE systems

The system interconnections with the UCTE synchronous area and the Nordel system are included in the generic model of the Danish power system, therefore the transmission capacities of these connections are taken into account. The transmission capacities between the eastern Denmark (Energinet.dk-east) and its neighbour countries are shown in Table 5-1. The transmission capacities between the western Denmark (Energinet.dk-west) and its neighbouring countries are shown in Table 5-2.

**TABLE 5-1**
**TRANSMISSION CAPACITIES OF THE EASTERN DANISH POWER SYSTEM** [10]

| Connections | Transmission Capacities (MW) |
|---|---|
| Sweden (AC) | 1700 |
| Germany (HVDC) | 600 |
| Energinet.dk-west (HVDC) | 600 |

**TABLE 5-2**
**TRANSMISSION CAPACITIES OF THE WESTERN DANISH POWER SYSTEM** [10]

| Connections | Transmission Capacities (MW) |
|---|---|
| Sweden (HVDC) | 540 |
| Norway (HVDC) | 1040 |
| Germany (AC) | 1400 |
| Energinet.dk-east (HVDC) | 600 |

## 5.2.1 Interconnections with Nordel

For the system interconnections with the Nordel system, power transaction with "hour-by-hour NEW Settlement Model" may start at the beginning of each hour or, when preferred, at the beginning of at least each quarter within the given hour. Figure 5-1 illustrates the present settlement model of the power transaction with the Nordel system. The transaction ends at the end of each hour and then the new transaction may begin. A transaction must start with the largest required power exchange and may be reduced each quarter of an hour within the given hour (a new bid). A transaction must not have any change in the direction of power flow within the give hour.

The characteristic time of the power ramp between different power levels of two different transactions would be 10 to 15 min. The power ramp between different power levels of two bids would be 15 min. [3]. It means that power exchange through the HVDC connections are made as hour by hour agreements, and there can only be some changes 3 times within an hour, and only in one direction. Therefore, the new settlement model introduces restriction on the use of the fast power control of the HVDC links.

However, this project focuses on the regulating power control within the Danish power system operation for the power balancing control at the Danish – German border. The domestic regulating power control generated from centralized thermal power plants, DCHP units, and the great belt link HVDC connection between the eastern and the western Denmark are of interested. Therefore, the power transaction between the Danish power system and the Nordel system is included in the Danish power system model as a time series data of planned power exchange. It is assumed that the HVDC connections with the Nordel system are operated according to their planned power exchange.

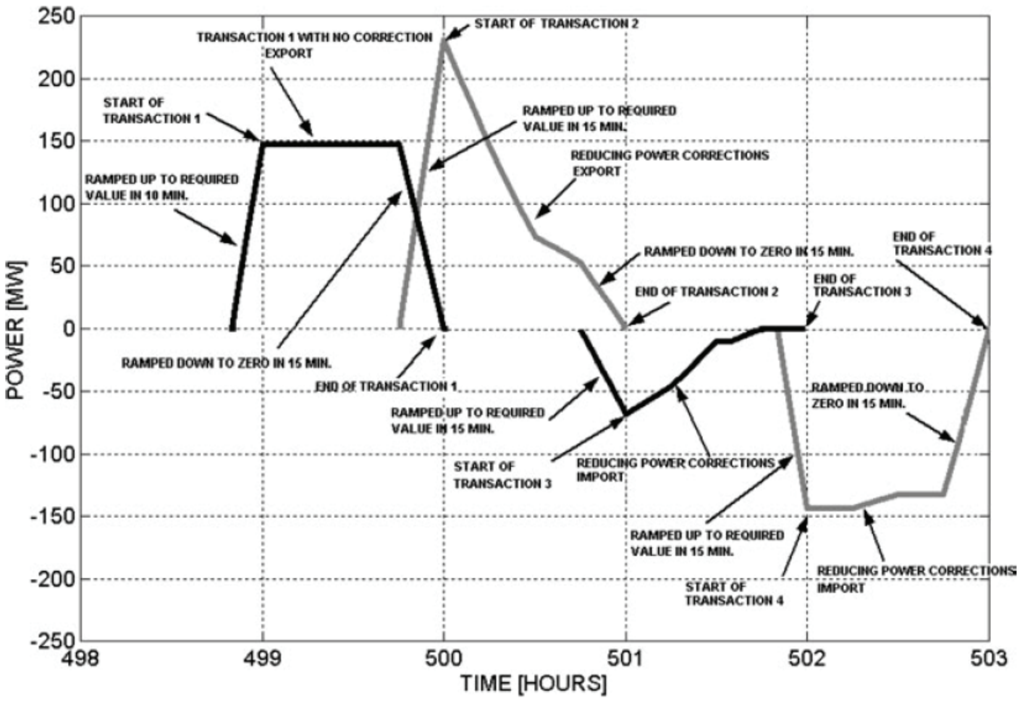


**Figure 5-1. Power transaction by using the settlement model of the power transaction with the Nordel system [2]**

## 5.2.2 Interconnections with UCTE

Imbalance caused by the wind power fluctuation generated from large scale wind farms may cause problem with power balancing control at the Danish – German border. The system interconnection between the western Danish power system and the UCTE system are modelled as a slack-bus with the negative load model of the planned power exchange (time series data) as shown in Figure 5-2. The summation of the planned power exchange ($P_{PLAN}$) and the deviation from planned power exchange ($P_{DEV}$) is the measurement of power transaction at the Danish – German border.

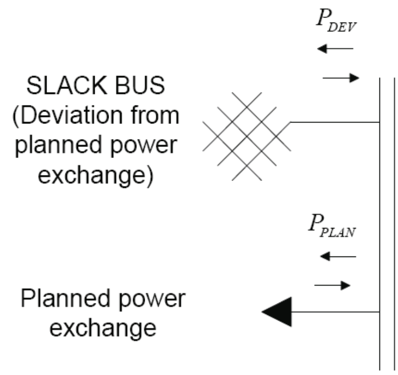


**Figure 5-2. A simplified model of the system interconnection with the UCTE system**

Besides the power fluctuations introduced by the wind farms, deviations from the planned power generation, demand and power exchange to the Nordel system contribute to the total deviations in the power exchange between the western Denmark and the UCTE synchronous area.

The deviation from the planned power exchanged with the UCTE interconnection becomes:

Total imbalance = Measured exchange - Scheduled exchange

or

$$P_{DEV} = P_{MEAS} - P_{PLAN} \tag{5-1}$$

The deviation from the planned power exchange ($P_{DEV}$) is the difference between the measured power ($P_{MEAS}$) and the planned power exchange ($P_{PLAN}$) with the UCTE system.

There are several ways to minimize such a power imbalance. The regulating power required can be ordered from the domestic power generating units. Still, there may be a small, residual power imbalance caused by the power gradient limits of the thermal power plants. This small, residual power imbalance will be transferred to the neighbouring areas or treated with the use of other control when available.

A power control system monitors the power exchange activity. When deviations from the planned power exchange are observed, the AGC system will adjust the available power production in the available power plants with regard to the planned power exchange via the HVDC connections. The overall model includes the power gradient limit and the necessary time constants of the processes and the response of the available power plants. With the use of the AGC system, the deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Balance} \qquad (5\text{-}2)$$

The deviations from the planned power $P_{DEV}$ between the measured power $P_{MEAS}$ and the planned power $P_{PLAN}$ with the UCTE system shall be minimized by the power balancing control $P_{Ctrl}^{Balance}$ .

# 5.3 Great Belt Link connection

Long-term and short-term power balances of the Danish transmission system, and keeping the power balance of the system interconnection with Germany (the UCTE system) is the main issue for the western Danish system. The utilization of the domestic regulating power resources is among the vital arrangements for better power balancing. This includes better utilization of local DCHP units, activation of the power control of the large offshore wind farms and avoiding making 'clusters' of large offshore wind farms.

Establishment of the GBL HVDC connection will make it possible to utilize the regulating power control incorporated in the eastern Denmark to work together with that established in the western Denmark. The GBL HVDC connection between the eastern and the western Danish power systems and its control is implemented in the power system model.

The GBL connection is developed based on several reasons such as large changes to the Danish electrical system during the last 10 years with regard to wind power and DCHP units, one TSO as Energinet.dk instead of two TSOs as Eltra and Elkraft system, and better power balance control with fast disturbance reserves and value of sharing disturbance reserves between eastern and western Denmark [14]. The cable would contribute to lower costs of electricity production as it will be possible to distribute production in a more optimum way. It would mean reduced requirements of reserves in the Danish electricity supply and also improve the scope for addressing imbalances in the power system between eastern and western Denmark. At the same time, the GBL will increase the robustness of the power supply in Denmark as it will give access to reserves from other parts of the country.

## 5.3.1 GBL power control

With the GBL connection, the utilization of the regulating power control incorporated in the eastern Denmark is expected to work together with that established in the western Denmark. The general diagram of the GBL regulating power control and the GBL power controller are shown in Figure 5-3 and Figure 5-4 respectively. This developed model can be used for long-term power system dynamic simulation considering the dynamics of the regulating power control capability.

When a large scale system is viewed as one system rather than a group of interconnected subsystems, the fast components of the large scale system become negligible compared to the slow components when a large time constant is considered. Therefore, a developed model of the regulating power control system of the GBL HVDC connection for long-term dynamic simulation is implemented and developed. For this purpose, the model consists of the dead band, controller time constant and ramp rate limiter. The model is based on simplifications of the regulating power control with regard to the dynamics of the ramp rate and the effect of the various modes of the overall power control.

The actual performance will depend on many factors such as the planned power exchange between the eastern and the western Denmark on the GBL connection, and the planned power exchange of the energinet.dk-east with Nordel system and UCTE system which will affect the dynamic performance in the total regulating power control. In this project, the regulating control of this model is seen from the western Denmark point of view.

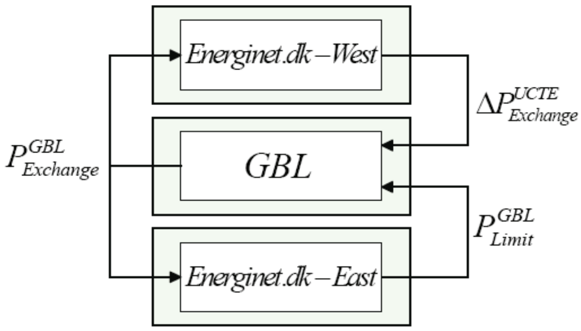


**Figure 5-3. GBL control diagram**

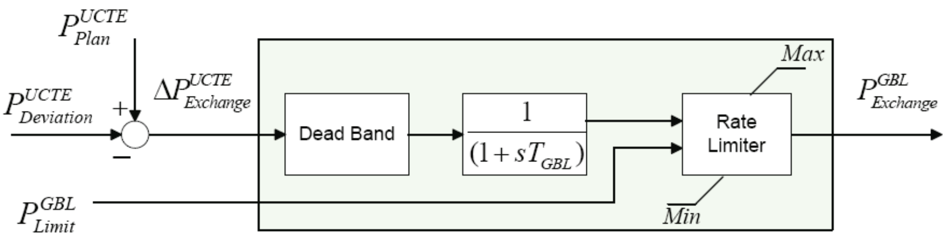


**Figure 5-4. GBL regulating power controller**

The GBL regulating power controller defines regulating power reference ($P^{GBL}_{Exchange}$) as function of the deviation from planned power exchange with the UCTE system ($\Delta P^{UCTE}_{Exchange}$) and the GBL regulating power limit ($P^{GBL}_{Limit}$) signals.

The TSO deliver the $P_{Limit}^{GBL}$ signal to the rate limiter block in response to the systems actual performance which depend on many factors such as the planned power exchange of the GBL connection, and the planned power exchange of the energinet.dk-east with Nordel system and UCTE system. The GBL power control is integrated in the AGC system as shown in Figure 5-5.

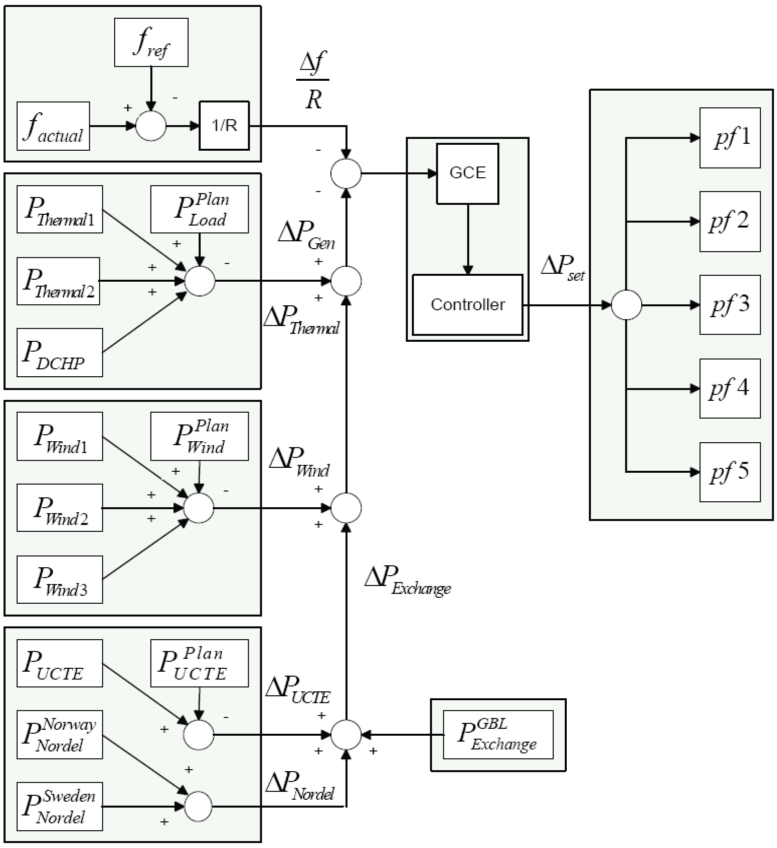


**Figure 5-5. AGC system with GBL regulating power control**

The simulation study of the utilisation of the regulating power control of the GBL HVDC connection will be carried with full flexible control strategy, with regard to the limitation on transmission capacity. The simulation study of the utilisation of the regulating power control of the GBL HVDC connection with regard to the planned power exchange between the energinet.dk-east and the UCTE system will be carried out in chapter 6.

### 5.3.2 GBL capacity limit

Energinet.dk plans a 600 MW cable link in the form of a traditional DC cable with converter stations as the eastern and the western Danish power system are not electrically synchronised. Conventional HVDC technology is chosen because the increased loss in a HVDC-VSC does not justify the added value of the HVDC light technology. The capacity of 600 MW is planned because the benefit is better suited for reserve reservation and future demand, and a larger unit size would increase the demand for reserves (the largest unit is 600 MW) [14].

The nominal loading of the link is 600 MW. It can be ramped down from 100% to 3% of the rated power very fast. The smallest ramping step is 1MW/min, but it can be ramped down/up as fast as 999MW/min. Such ramping is smooth in the range -100% to -3%, -3% to -100% and 100% to 3%, 3% to 100%. The lowest loading of the GBL can be 3%. Below 3% loading, it must be switched off and start up again from -3%, in the opposite direction. The ramping is smooth in every case except in the range 3% to 0 to -3%.

The power flow direction can be reversed by turning off the HVDC link and restart it in the opposite direction with the minimum loading of 3%. The time constant of changing the power flow direction is included in the power regulating control of the GBL connection. Time constant of changing the power flow direction from +3% to -3% is approximately 500 ms and from +50% to -50% is approximately 700 ms. An emergency power control in the control system, in case of some problems in the network, can shut down the HVDC link faster than 999MW/min [39].

Parameters of the GBL regulating power control are shown in Table 5-3. $P_{East-Limit}^{GBL}$ is the available regulating power on energinet.dk-east which depend on the planned power exchange of the GBL connection, and the planned power exchange of the energinet.dk-east with Nordel system and UCTE system. In this project, the model is developed with regard to the regulating power control, seen from the western Danish system point of view. The emergency shut down of the HVDC link is not included in this model.

**TABLE 5-3**
**CONTROL PARAMETERS OF GBL POWER CONTROLLER** [39]

| Parameters | Value |
|---|---|
| Capacity | 600 MW |
| Dead Band | $\leq$ -18 MW / $\geq$ 18 MW |
| $T_{GBL}$ | 500 ms – 700 ms |
| Maximum Rate Limiter | 999 MW/min |
| Minimum Rate Limiter | 1 MW/min |
| $P_{East-Limit}^{GBL}$ | 1300 MW |

# 5.4 Summary

In this chapter, the characteristics and control topology of the system interconnections with the UCTE area and the Nordel system are presented. An overview structure and technical requirement of the great belt link HVDC connection are described. The new settlement model introduces restriction on the use of the fast power control of the HVDC connections with the Nordel system. It can be seen that the power exchange through the HVDC links with the Nordel system is limited with the new settlement model. Therefore, the better and more intense use of domestic regulating power is required. This project is focus on the regulating power control within the Danish power system operation for the power balancing control at the Danish – German border. The domestic regulating power control generated from centralized thermal power plants, DCHP units, and the great belt link HVDC connection between the eastern and the western Denmark are of interested. Therefore, the power transaction between the Danish power system and the Nordel system is included in the Danish power system model as a time series data of planned power exchange. It is assumed that the HVDC connections with the Nordel system are operated according to their planned power exchange.

The system interconnection between the western Danish power system and the UCTE system are modelled as a slack-bus with the negative load model of the planned power exchange (time series data). Imbalance caused by the wind power fluctuation generated from large scale wind farms may cause problem with power balancing control at the Danish – German border. Therefore, the deviation from planned power exchange can be illustrated on this slack-bus.

An overview of the great belt link HVDC connection between the eastern and the western Danish systems and its regulating power control model are presented. In this project, the limit of regulating power control from the eastern Denmark via the GBL is restricted with the deviation of planned power exchange between the energinet.dk-east and the Nordel system via the AC cables. The utilization of the regulating power control incorporated in the eastern Denmark to work together with that established in the western Denmark is expected.

# Chapter 6
# Control Strategies

## 6.1 Introduction

In this chapter, models of the domestic power generating units in the Danish power system that were described in chapter 3, chapter 4, and chapter 5 are derived based on their regulating power control capability. The rapid power fluctuations generated from wind farms will contribute to imbalance between power generations and consumptions in the Danish power system. Imbalance caused by the wind power fluctuation generated from large scale wind farms also cause problem with power balancing control at the Danish – German border. Therefore, a power balancing control should be developed to manage the imbalance taking into account the uncertain nature of wind power. The total generic model is expected to be used to evaluate the active power balance control and long-term power system stability with different control strategies at different load and production conditions.

The power fluctuation generated from the offshore wind farm may give a significant contribution to the deviation from the planned power exchange between the western Denmark and Germany. The western Danish power system is subjected to transits between two synchronous areas operated on different conditions. The power exchange with the Nordel system is arranged through the HVDC connections and controlled each 15 minutes. On the other hand, the planned power exchange with the UCTE system is controlled each 5 minutes [2]. This introduces a challenge with regard to keeping the power balance in the Danish power system and complying with planned power exchange with the Nordel and the UCTE systems.

This project focuses on solving the power imbalance caused by rapid power fluctuations observed in the offshore wind farms and also to examine the ability of the secondary control of the power generating units to reduce the affect caused by wind power fluctuations in the Danish power system. The utilization of the regulating power control of the domestic power generating units is examined. The power generation control of different power generating units with regard to ramp rate and the units' time response is taken into account. The utilization of the regulating power control in the eastern Denmark via the GBL connection and how to make it work together with that established in the western Denmark is demonstrated.

# 6.2 Power balancing control

Imbalance caused by the wind power fluctuation generated from large scale offshore wind farms may cause deviations from the planned power exchange between Denmark and Germany. Complying with the total regulating power implies that the deviations in the power exchange with the UCTE system is kept within an acceptable limit, but not necessary to be completely eliminated [3]. Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generating units. These include the secondary control of the thermal power plants, as well as the secondary control provided from the DCHP units, to smooth out fluctuating power from wind generators and increase the overall reliability of the power system.

The main target here is to keep the power generation in balance to the power consumption and to keep the power exchange between the western Danish power system and the UCTE system at the planned power exchange. Earlier studies in [3], [8], [17] and [42] have shown that the power exchange through the HVDC links with the Nordel system is limited with the new settlement model. Therefore, a better and more intense use of domestic regulating power is required. The identification of technical problems, which might set up a limit for the wind turbine power penetration on the transmission level, should be examined. Power gradient and delta control of the wind farm and the secondary control from DCHP unit should be used to maintain the power deviation within an acceptable range. Power gradient response over a period of several seconds and minutes can be significant to system behaviour following disturbances resulting in significant imbalance between generations and loads.

The technical arrangements and proposed control strategies here are the use of an area controller with activation of the secondary control of the thermal power plants, utilisation of the fast secondary control from the DCHP units, utilisation of the power gradient limit and the delta control in the wind farm, and the utilisation of the regulating power control of the GBL HVDC connection.

## 6.2.1 Domestic power generating units

Most of the large thermal power plants in Denmark are coal-fired CHP units that can extract steam for heat production and which have an operating domain between 20% and full power load without heat production [2]. The thermal power generating units have a ramping capability of full load per minute in different operating ranges. These thermal power plants are separated into groups performing slow and relatively fast secondary control respectively with regard to their ramp rate limiter and units' time response. In this project, the thermal power plants are separated into 4 groups which have different ramp rate and units' time response as specified in Table 4-3 and Table 4-4.

Most of DCHP units are based on gas turbine technology as described in Chapter 3. These units are equipped with heat storage tank, so they can operate more independently from the heat demand. The small DCHP units with below 10 MW operate normally as on-off controlled depending on the tariffs. From January 2005, the DCHP units, with above 10 MW rated power, are involved to participate in the regulating power market and contribute to the power balance in the system [2]. The utilization of the domestic regulating power resources as DCHP units is among the vital arrangement for better power balance control. In this project, DCHP units with above 10 MW rated power are integrated within the AGC system, therefore the regulating power can be ordered upon request.

### 6.2.2 System control strategies

The deviation between the forecast planned power to be supplied and the power generation from the HRA offshore wind farm, with 160 MW rated power, is shown in Figure 6-1. Commissioning of the new offshore wind farm HRB, with 215 MW rated power, in the same geographical area as the HRA wind farm will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange within the period of some minutes to one hour. Large power deviation in the range of more than +/- 50MW can be expected [2]. Therefore, the regulating power and control strategies are needed to prevent such a large power deviation in the future. The deviation from the planned power exchange with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Balance} \tag{6-1}$$

That is, the deviations power ($P_{DEV}$) between the measured power exchange ($P_{MEAS}$) and the planned power exchange ($P_{PLAN}$) with the UCTE system shall be minimized by the secondary control of the power generating units ( $P_{Ctrl}^{Balance}$ ).

The utilization of the regulating power from the domestic power generating units is investigated. The simulation studies based on different control strategies, as shown in Table 6-1, have been carried out. First, the utilization of centralized thermal power plants with the secondary control of the available thermal power plants is carried out. Second, the utilization of DCHP units with the use of the secondary control of the available power plants and the utilization of the secondary control from DCHP units is presented. Then, the utilization of wind power control with the use of the power gradient limit together with Delta control on HRA wind farm, the secondary control of the available power plants and the additional use of the secondary control from DCHP units is carried out. Finally, the large power fluctuation is introduced by the commissioning of the new offshore wind farm HRB. Therefore, the utilization of regulating power control via the GBL HVDC connection is demonstrated.

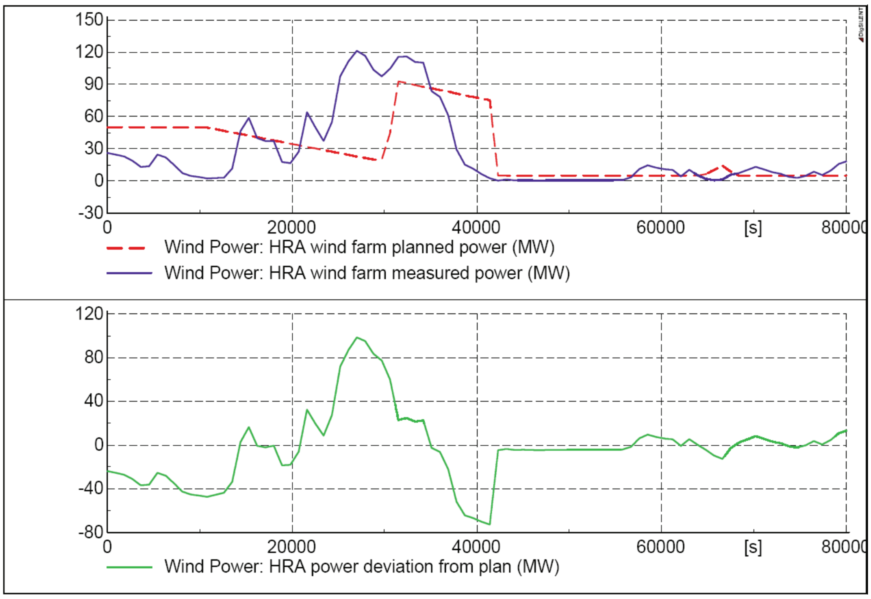


**Figure 6-1. Forecast and measured power from HRA wind farm (above) and power deviation from planned wind power (below)**

**TABLE 6-1**
**SYSTEM CONTROL SCENARIOS IN POWER BALANCING CONTROL**

| Case | Control strategies |
|---|---|
| 1 | The secondary of thermal power plants<br>The DCHP units are operated as their plan |
| 2 | The secondary of thermal power plants<br>The secondary of DCHP units |
| 3 | The secondary of thermal power plants<br>The secondary of DCHP units<br>The Delta control of wind farm |
| 4 | The secondary of thermal power plants<br>The secondary of DCHP units<br>The regulating power control from the GBL |

## 6.3 The utilization of domestic generating units

### 6.3.1 The utilization of centralized thermal power plants (case 1)

In this simulation study, the measured power from HRA in Figure 6-1 is rescaled to 160 MW as shown in Figure 6-2 to give a kind of worst case scenario. Figure 6-3 shows the simulated result of the power deviation computed with the use of the power gradient limit on wind farm HRA and the use of the secondary control of the available thermal power plants in Table 6-2, where the DCHP units are not subject to the orders from the area controller, as they are operated according to the market conditions (tariffs) and do not contribute to the power balance control. The deviation from the planned power exchanged with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Thermal} \tag{6-2}$$

The deviations from the planned power exchange ($P_{DEV}$) between the measured power exchange ($P_{MEAS}$) and the planned power exchange ($P_{PLAN}$) with the UCTE system shall be minimized by the secondary control of the thermal power plants ( $P_{Ctrl}^{Thermal}$ ).

Figure 6-4 and Figure 6-5 show the simulation results of the generation from the 4 thermal power plants and time series data of the DCHP generations respectively. The time series data of power transaction with the Nordel system and loads are illustrated in Figure 6-6 also used as input. A dynamic simulation of the developed thermal power plant model with given time series data of DCHP generations, loads, and power exchange with the Nordel system, on a day in 2003 is demonstrated. This analysis has shown the capability of the available thermal power plants which nearly eliminate the power deviations from planned power exchange with the UCTE system.

**TABLE 6-2**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (second) | *pf* |
|---|---|---|---|---|---|---|---|
| Plant 1 | 1684 | 2 | 2 | 4 | 2 | 210 | 0.25 |
| Plant 2 | 700 | 1.5 | 2 | 4 | 2 | 210 | 0.25 |
| Plant 3 | 392 | 2 | 2 | 8 | 2 | 210 | 0.25 |
| Plant 4 | 625 | 2 | 2 | 4 | 2 | 330 | 0.25 |

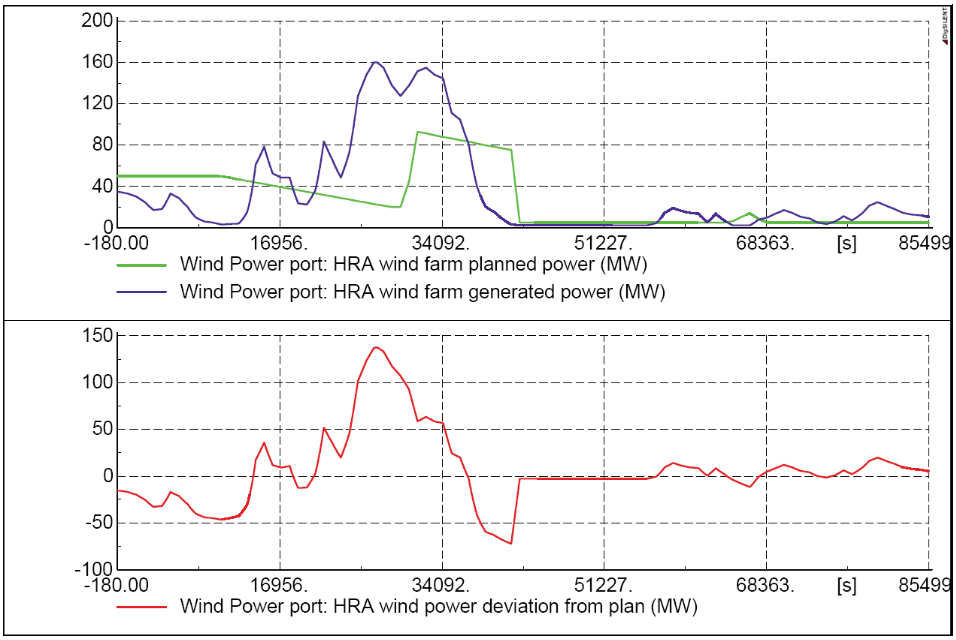


**Figure 6-2. Rescaled power generation from HRA wind farm (above) and deviation from planned wind power (below)**

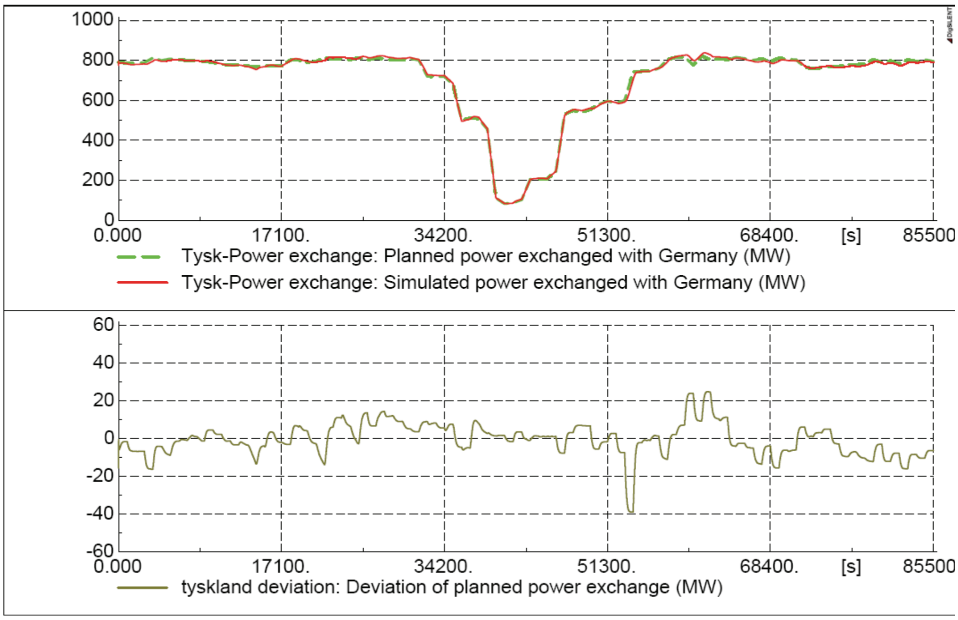


**Figure 6-3. Power exchange with, Germany (above) and power deviation from plan (below) when the secondary control of thermal power plants is applied (+import/-export)**

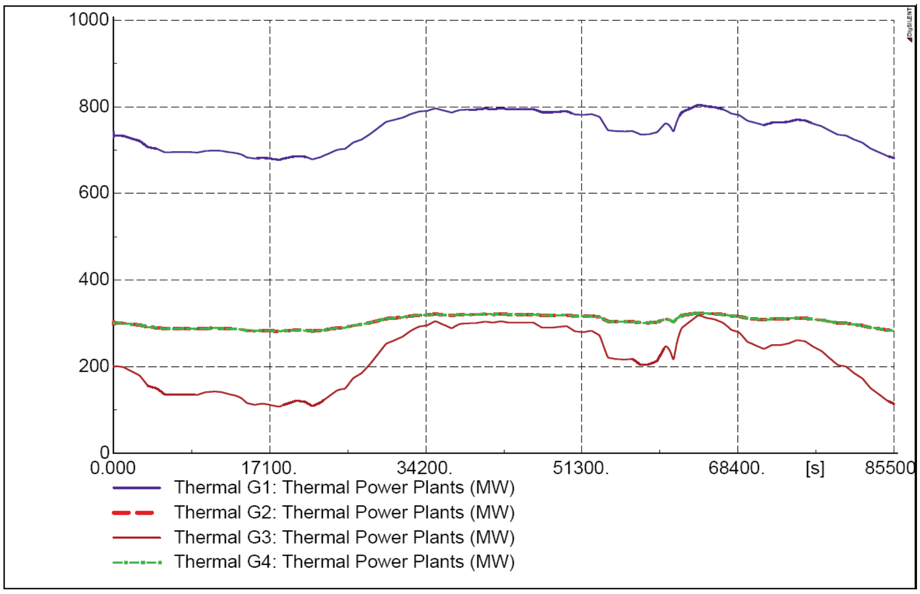


**Figure 6-4. Power generation from 4 aggregated power plants with AGC system**

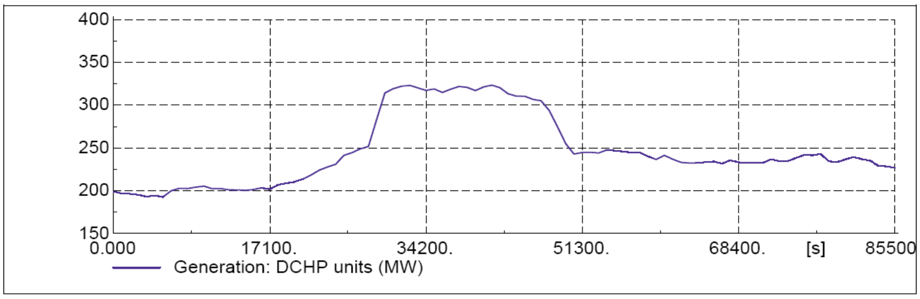


**Figure 6-5. Power generation from DCHP units (time series data) [10]**

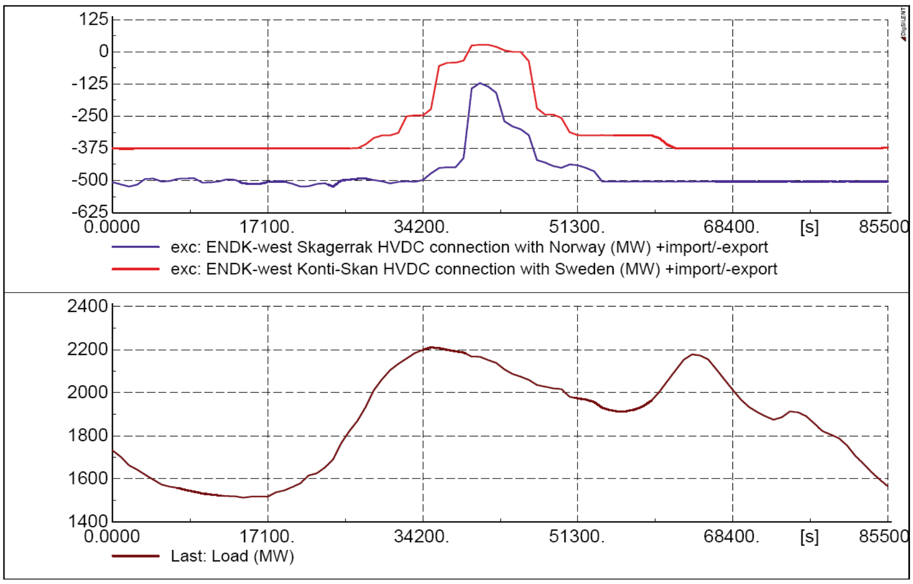


**Figure 6-6. Power transaction with Nordel system and loads (time series data) [10]**

### 6.3.2 The utilization of DCHP units (case 2)

The same day in 2003 is again simulated. In this simulation, the effect of using the secondary control from the DCHP units is illustrated. These include the secondary control of the thermal power plants, as well as the secondary control from the DCHP units, to smooth out fluctuating power.

Figure 6-7 presents the resulting power deviation at the western Danish-German border with the use of the power gradient limit on wind farm HRA, the use of the secondary control of the available power plants and the utilization of the secondary control ( $P_{Ctrl}^{DCHP}$ ) from DCHP units. Figure 6-8 shows the simulation result of the power generation from DCHP units and thermal power plants. This analysis has shown the even better capability of the available regulating power which decreases the power deviations with the UCTE system even more. The deviation from the planned power exchanged with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Thermal} - P_{Ctrl}^{DCHP} \tag{6-3}$$

In this simulation study, the DCHP units, with above 10 MW rated power, are involved to participate in the regulating power market and contribute to the power balance control, as shown in Table 6-3, to illustrate the units' response when operated with the AGC system. It can be seen that the responses of the aggregated DCHP unit is different from the time series of DCHP generation as operated depending on tariffs, due to the use of the fast secondary control and the incorporation with AGC system.

**TABLE 6-3**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | *pf* |
|---|---|---|
| Plant 1 | 1684 | 0.25 |
| Plant 2 | 700 | 0.25 |
| Plant 3 | 392 | 0.25 |
| Plant 4 | 625 | 0.20 |
| DCHP | 400 | 0.05 |

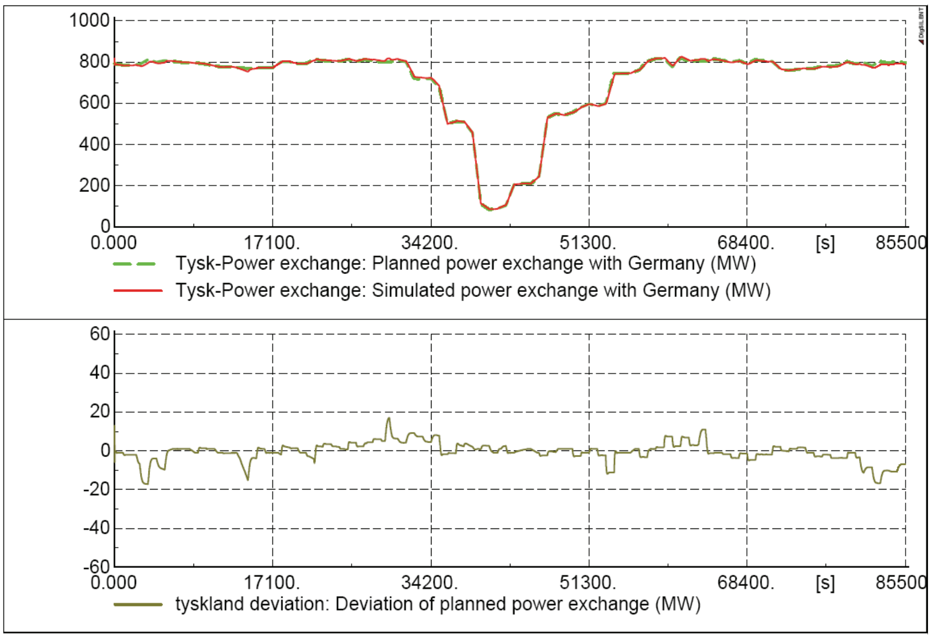


**Figure 6-7. Power exchange with, Germany (above) and power deviation from plan (below) when the secondary control of thermal power plants and the secondary control of DCHP units is applied (+import/-export)**

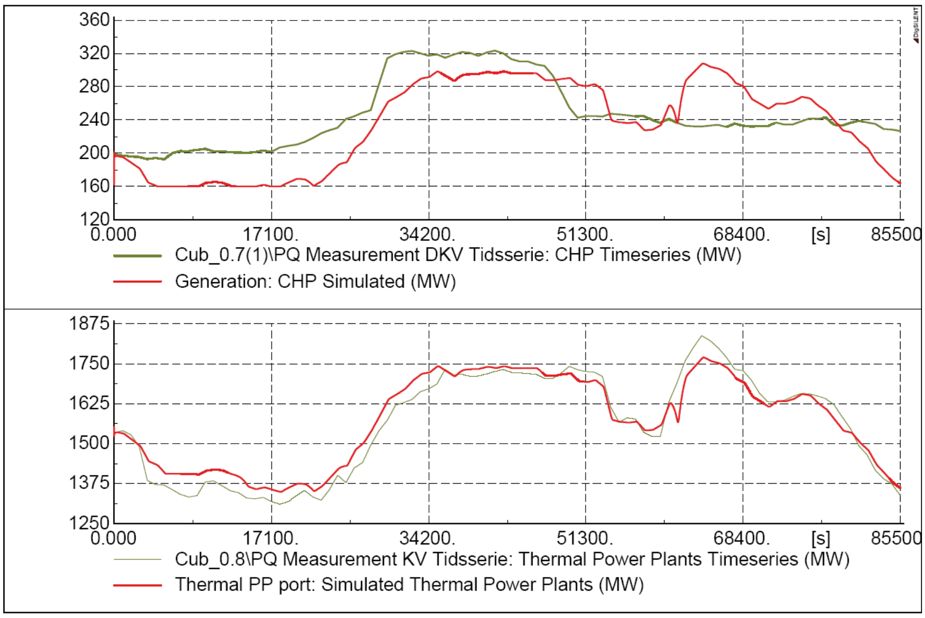


**Figure 6-8. Comparison between time series data and power generation from DCHP units, operated with the AGC system (above) and comparison between time series data and power generation from thermal power plants (below)**

### 6.3.3 The utilization of wind power control

The same day in 2003 is again simulated. In this simulation, the effect of using the secondary control from the DCHP units and the delta control of wind farm is illustrated. The power gradient and delta control of the wind farms and the secondary control from DCHP units are developed to maintain the power deviation within the acceptable range.

Figure 6-9 presents the resulting power deviation at the western Danish - German border with the use of the power gradient limit together with Delta control on HRA wind farm, the secondary control of the available power plants and the additional use of the secondary control from DCHP units. The deviation from the planned power exchanged with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Thermal} - P_{Ctrl}^{DCHP} - P_{delta}^{WF} \tag{6-4}$$

The deviations power ($P_{DEV}$) between the measured power ($P_{MEAS}$) and the planned power ($P_{PLAN}$) with the UCTE system shall be minimized by the power balancing control $P_{Ctrl}^{Thermal}$, $P_{Ctrl}^{DCHP}$ and delta control ( $P_{delta}^{WF}$ ) from HRA wind farm.

Figure 6-10 shows the comparison of power deviations at the western Danish-German border between the use of the secondary control of DCHP unit and the use the secondary control of DCHP with Delta power control on HRA wind farm. This analysis has shown the slightly better capability of the available regulating power which decreases the power deviations from the planned power exchange with the UCTE system. It can be seen that the delta control did not reduce the fluctuation at all times due to the fast secondary control of DCHP units.

**TABLE 6-4**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | *pf* |
|---|---|---|
| Plant 1 | 1684 | 0.25 |
| Plant 2 | 700 | 0.25 |
| Plant 3 | 392 | 0.25 |
| Plant 4 | 625 | 0.20 |
| DCHP | 400 | 0.05 |
| HRA wind farm | - | 0.05 |

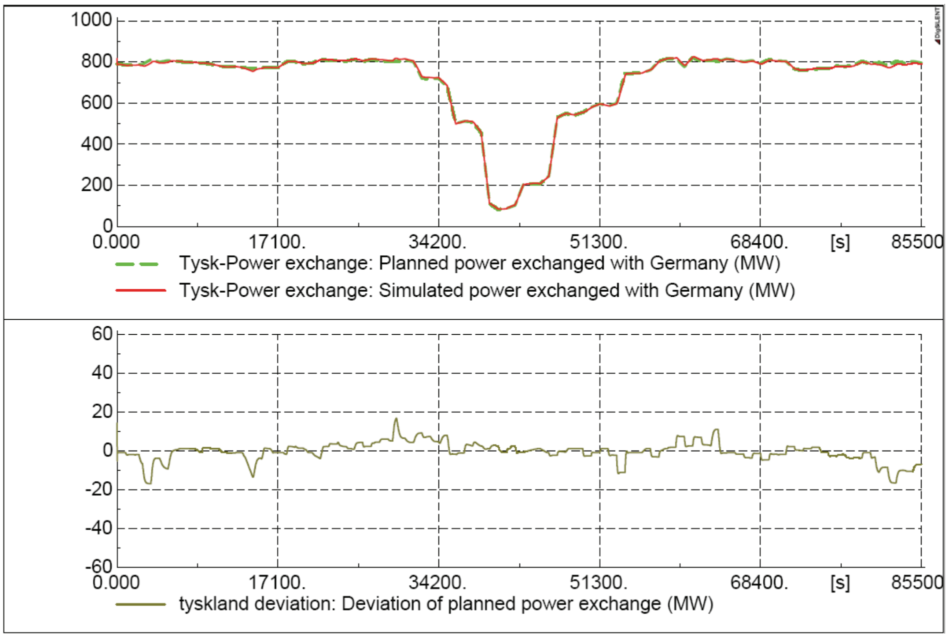


**Figure 6-9. Power exchange with, Germany (above) and power deviation from plan (below) when the secondary control of DCHP units and the delta control of wind farm are applied (+import/-export)**

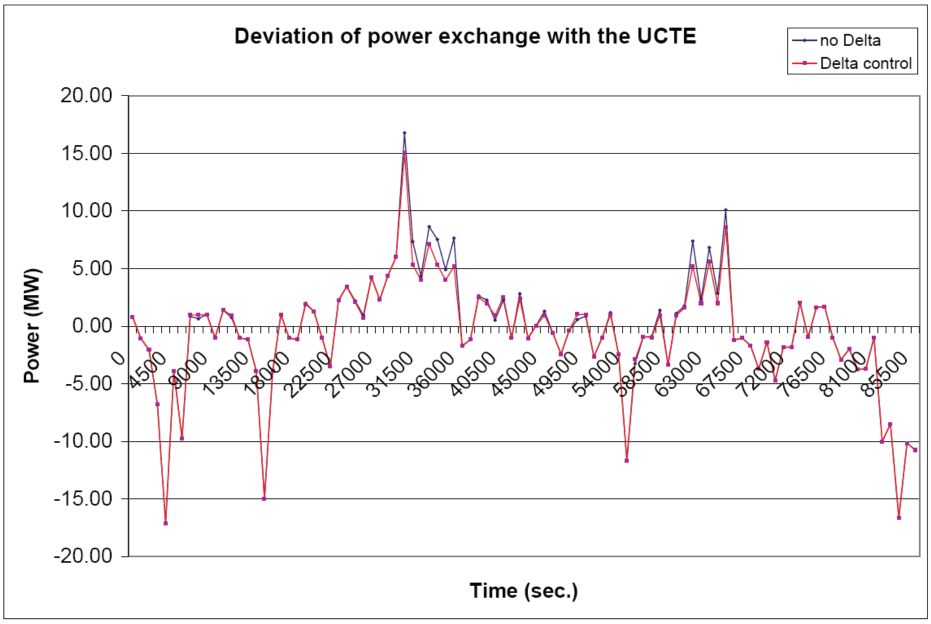


**Figure 6-10. Comparison of power deviation when the secondary control of DCHP units is applied (blue) and when the secondary control of DCHP units and the delta control of wind farm are applied (red)**

## 6.4 The utilization of the GBL connection (case 4)

The simulation study of the utilisation of the regulating power control of the GBL HVDC connection is carried out with full flexible control strategy, with regard to the transmission capacity limit, the planned power exchange of the GBL connection, and the planned power exchange of the energinet.dk-east with Nordel and UCTE systems. Commissioning of the new offshore wind farm HRB with 215 MW rated power, in the same geographical area with the HRA wind farm will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange within the period minutes to one hour. Large power deviation from the planned power exchange can be expected. Therefore, the regulating control and control strategies are needed to prevent such a large power deviation in the future. Complying with the total regulating power implies that the deviations in the power exchange with the UCTE system is kept within an acceptable limit.

In this simulation study, the simulated power from the HRB is rescaled to 215 MW and the output is correlated with the output from HRA as shown in Figure 6-11. Figure 6-12 presents the resulting power deviation at the western Danish-German border with the use of the power gradient limit on wind farm HRA, and the use of the secondary control of the available power plants. Power balance control with all the above functions, together with the additional use of the spinning reserve from DCHP units is presented as shown in Figure 6-13. This analysis has shown the even better capability of the available regulating power which decreases the power deviations from the planned power exchange with the UCTE system. The deviation from the planned power exchanged with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Domestic} \tag{6-5}$$

The deviations power ($P_{DEV}$) between the measured power ($P_{MEAS}$) and the planned power ($P_{PLAN}$) with the UCTE system shall be minimized by the regulating power control from domestic sources ( $P_{Ctrl}^{Thermal} + P_{Ctrl}^{DCHP}$ ).

**TABLE 6-5**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | *pf* |
|---|---|---|
| Plant 1 | 1684 | 0.25 |
| Plant 2 | 700 | 0.25 |
| Plant 3 | 392 | 0.25 |
| Plant 4 | 625 | 0.20 |
| DCHP | 400 | 0.05 |

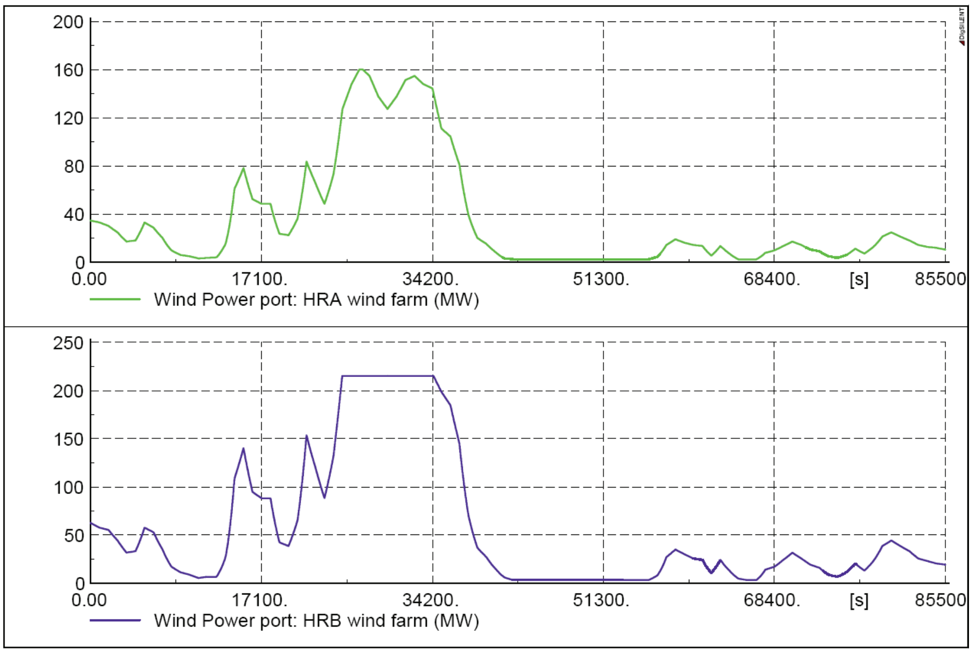


**Figure 6-11. Power generation from HRA wind farm (above) and from HRB wind farm (below)**

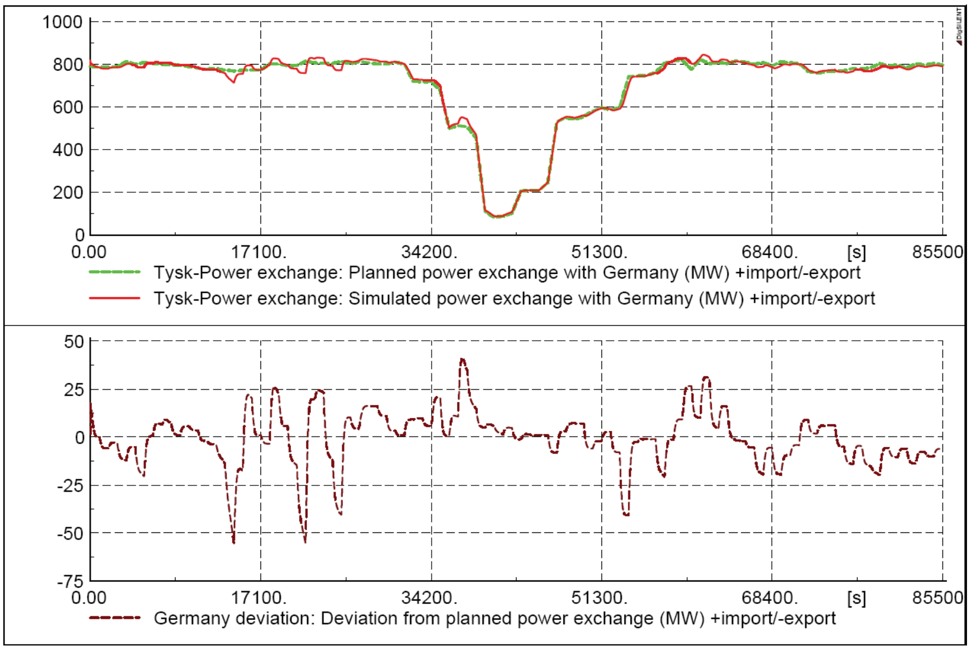


**Figure 6-12. Power exchange with, Germany, the UCTE system (above) and power deviation from plan (below) when the secondary control of centralized power plants are applied**

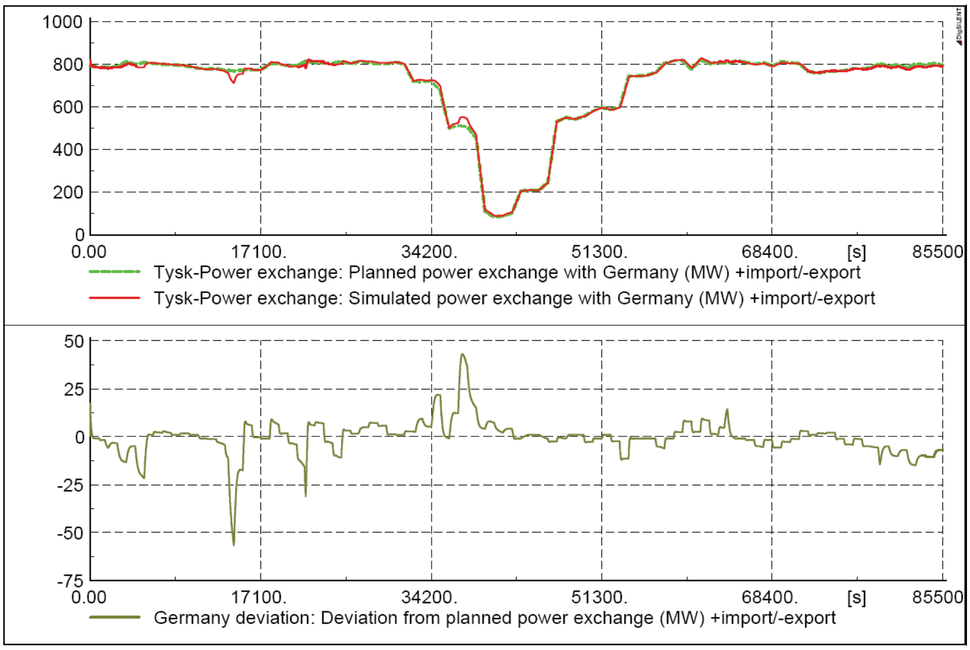


**Figure 6-13. Power exchange with Germany (above), Power deviation from plan (below) when the secondary control of centralized power plants and the secondary control from DCHP unit are applied**

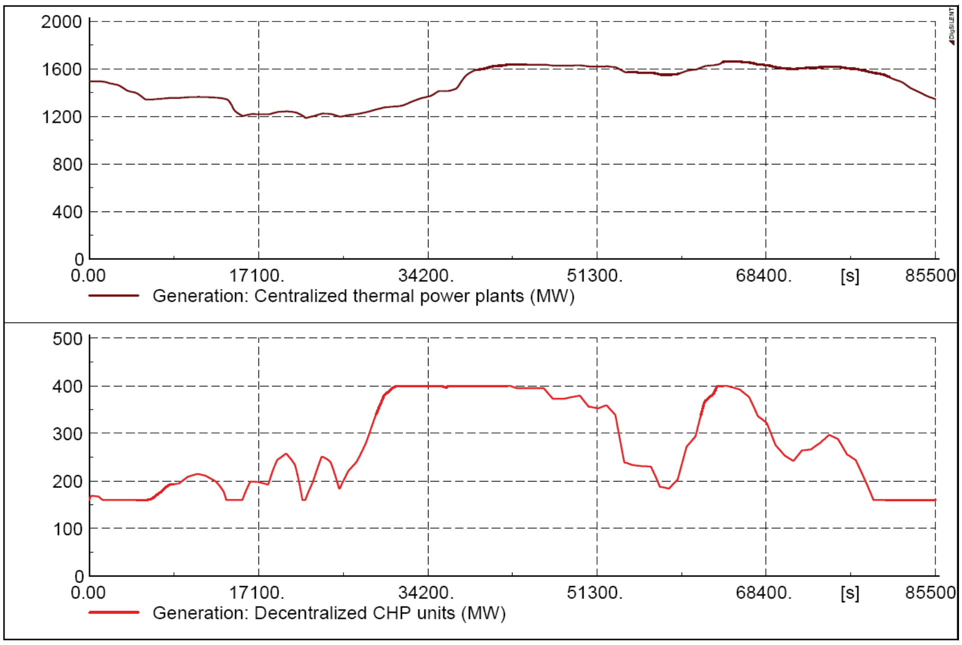


**Figure 6-14. Power generations from centralized power plants (above), and power generations from DCHP units in AGC system**

In Figure 6-13, the resulting power deviation at the western Danish-German border with the use of the secondary control of the thermal power plants and the additional use of the secondary control from DCHP units is presented. Still, there is a small, residual power imbalance caused by the power gradient limit of the power generating units. With the GBL connection, the utilization of the regulating power control incorporated in the eastern part of Denmark is expected to work together with that established in western Denmark. The deviation from the planned power exchanged with the UCTE interconnection becomes:

$$P_{DEV} = P_{MEAS} - P_{PLAN} - P_{Ctrl}^{Domestic} - P_{Ctrl}^{GBL} \tag{6-6}$$

The deviations from the planned power ($P_{DEV}$) between the measured power ($P_{MEAS}$) and the planned power ($P_{PLAN}$) with the UCTE system shall be minimized by the domestic power regulating control ($P_{Ctrl}^{Domestic}$) which consist of $P_{Ctrl}^{Thermal}$ and $P_{Ctrl}^{DCHP}$, and the regulating power control via GBL connection ($P_{Ctrl}^{GBL}$).

Figure 6-15 presents the resulting power deviation at the Danish-German border with the use of the AGC system accessing the secondary control of the thermal power plants, the secondary control of the DCHP units and the regulating power from the GBL HVDC connection. The GBL connection is able to provide almost instantaneous power control on demand within a limited range. The regulating power control provided from the GBL is illustrated in Figure 6-16.

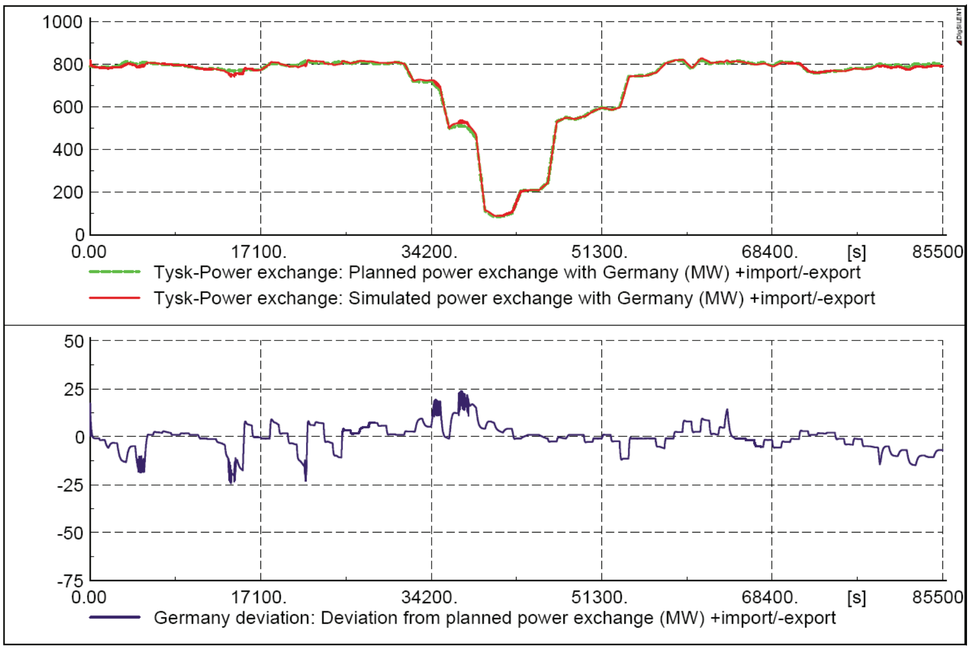


**Figure 6-15. Power exchange with Germany (above), Power deviation from plan (below) when the regulating power control of the GBL connection is applied**

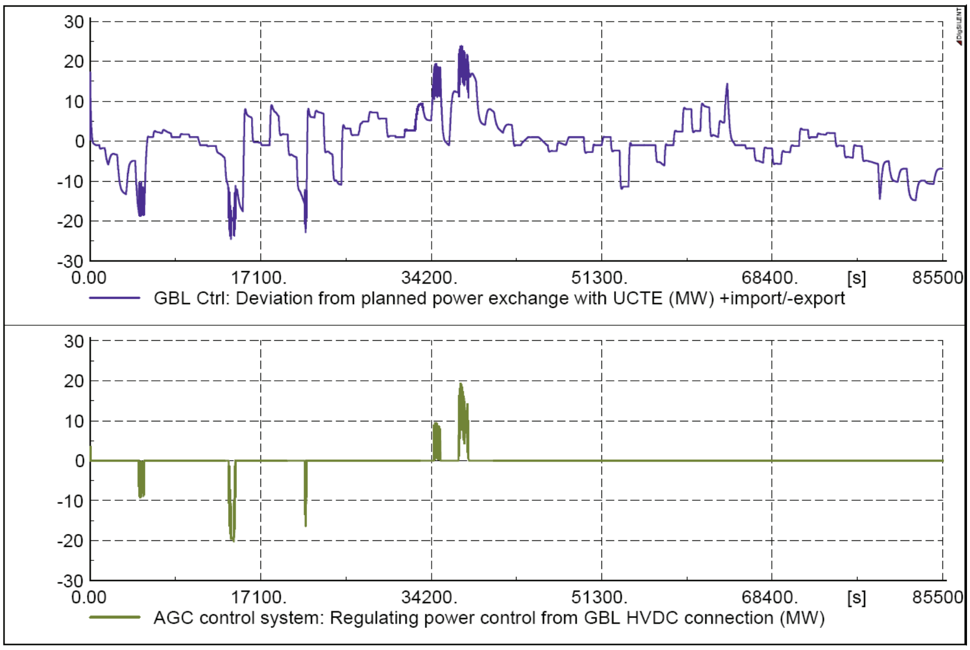


**Figure 6-16. Deviation from planned power exchange with the UCTE when the GBL control is activated (above), and the regulating power control from GBL (below)**

From Figure 6-16, it can be seen that the regulating power control provided from the GBL HVDC connection is activated when the deviation from planned power exchange is larger than +/- 18 MW with regard to the technical specification on Table 5-3.

Figure 6-17 presents the comparison between the deviations from the planned power exchange at different control strategies. Simulation results from control strategies case 1, case 2 and case 4 are compared. It is shown that the regulating power control from the GBL connection can almost eliminate the fluctuation and the small residual can be kept in limit. It can also be concluded that the limit of wind power penetration can also be analyzed with regard to the specified control strategies and the regulating power capability of generation units together with the regulating power control from the interconnected systems.

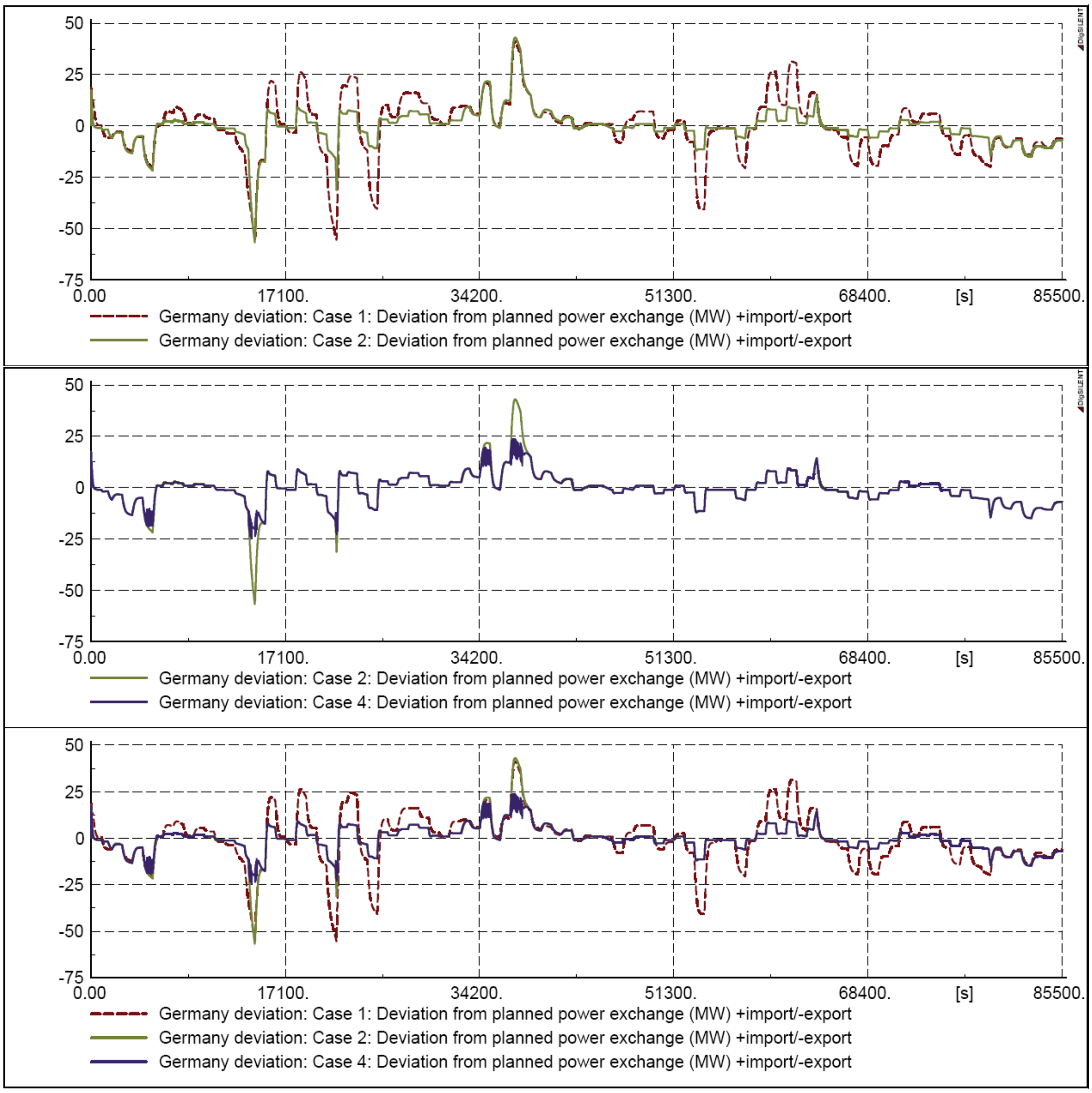


**Figure 6-17. Comparison between the deviations from the planned power exchange of different control strategies**

## 6.5 Summary

In this chapter, the impacts of power fluctuations from large scale wind farms on the power system with regard to the power balance control have been presented and discussed with different control strategies. The utilization of the domestic regulating power resources is among the vital arrangements for better power balancing. This includes the secondary control from the centralized power plants, the utilization of the secondary control from the DCHP units and activation of the power control of the offshore wind farms which includes the power gradient limit and the delta production control.

The utilization of the centralized thermal power plants with the secondary control of the available thermal power plants is carried out. This analysis has shown the capability of the available thermal power plants which nearly eliminate the power deviations from the planned power exchange with the UCTE system. Then, the utilization of the secondary control of the available centralized power plants and the utilization of the secondary control from DCHP units are also carried out. The analysis has shown the even better capability of the available regulating power which decreases the power deviations with the UCTE system even more. The utilization of wind power control with the use of the power gradient limit together with Delta control on HRA wind farm is presented. The analysis has shown the slightly better capability of the available regulating power which decreases the power deviations with the UCTE system.

The simulation study with the commissioning of the new offshore wind farm HRB, in the same geographical area with the HRA wind farm is carried out. The establishment of the GBL make it possible to utilize the regulating power control incorporated in the eastern Danish system to work together with that established in the western Danish system. The utilization of the AGC system accessing the secondary control of the thermal power plants, the secondary control of the DCHP units and the GBL HVDC connection is demonstrated. This analysis has shown the better capability of the available regulating power which decreases the power deviations with the UCTE system. It can be concluded that the wind power characteristics and power system operation strategies, which allows for active power balance might set up a limit for the wind power penetration.

# Chapter 7

# Evaluation of the Simulation Results

## 7.1 Introduction

This chapter first gives an introduction to why sensitivity analysis tested should be used for the control parameters in the power generating units in the AGC system to see how it affects the power system operation. An overview of the dynamic sensitivity analysis is given in a simulation study of the centralized thermal power plants and their units' response is presented. Various simulation studies of the power system operation based on different control issues are carried out.

The main part of this chapter is devoted to the evaluation of the simulation results by the dynamic sensitivity analysis. First, a simulation study of the conventional thermal power plants, based on their different characteristics in ramp rate and boiler time constant, is presented and described. Then, the dynamic sensitivity analyses on the power system operations are carried out. Simulation studies with different share of the centralized power plants and the decentralized combined heat and power units are presented. Finally, an N-1 analysis with regard to power balancing control issue is also given.

The impacts on power system operations of the different control parameters in various simulation studies are discussed. It can be seen that sensitivity analysis is used to rank the inputs that are responsible for a drastic change in the outputs and that it can also be used to list the outputs which are most affected by the change in the input. The sensitivities of the outputs with respect to the input parameters of the ramp rate limiter and boiler time constant in the thermal power plants and the participation factor in the AGC system are analyzed. It is pointed out that the difference between the responses of thermal power plants is mainly caused by the ramp rate limiter in a boiler turbine control and the boiler time constant in a thermal boiler. The influence of the chosen *pf* values in the AGC system for power balancing control is also presented.

# 7.2 Dynamic sensitivity analysis

Several dynamic models have been developed to perform simulation and control tasks. The models are used to gain some insight into possible outcomes, which are later used in developing real time applications in power system operation. However, before these models are used in the real world, there is a need to study their sensitivity. This section shortly addresses the use of sensitivity analysis to investigate the sensitivity of the parameters in the developed models, which are used in long-term dynamic simulation. The computed sensitivities can be used to rank the critical inputs that are responsible for a drastic change in the outputs. Sensitivities can also be used to list the outputs which were most affected by the change in the input.

Sensitivity analysis is an important component in building simulation models. The values of model parameters, the computations, and the input values of variables are prone to many sources of uncertainty. It is necessary to understand the sensitivity of a model's outputs to the changes in the model's inputs [43]. Sensitivity analysis experiments may be performed on mathematical and computational models to determine the sensitivity of model outputs to the uncertainty of input variables, computations, and parameter values [44]. The results from dynamic sensitivity analysis can be used for various purposes, such as for ranking the inputs and parameters with regard to their relative sensitivity to the output, for assessing changes in the output due to parameter and input variations, and for limiting the use of the program to regions where it is stable. By conducting this study, parameters or input values which have the greatest effect on the model outputs can be indicated.

The main concern is gaining insight into the behaviour of the model or computational procedure. One approach to sensitivity analysis is to compute dependent variable of outputs with respect to independent variable of inputs in a model. The dynamic models are often expressed as systems of equations, which relate the dependent variables to the independent variables. This system is a dynamic model developed to present the dynamic behaviour of a power system. It is important to understand a system both mathematically and physically to replicate the physical system's actual behaviour [45]. A dynamic model of the power system has been developed to analyze the actual dynamics involved in the system. The input parameters of the model are the dynamic states of the power system. The outputs are states of the system, such as power productions from generating units, power transactions between different areas.

However, this project focuses on power balancing control, especially on the deviation from planned power exchange at the Danish – German border. The sensitivity analysis is, therefore, carried out with regard to the power balancing control issue. In the analysis of power generating units, the unit response with regard to input parameters of the model is taken into account. Different degree of units' responses is used to indicate the sensitivity of input parameters in the thermal power plant model. In power system operation analysis, the deviation from the planned power exchange between Denmark and Germany (UCTE system) is used to indicate the sensitivity of input parameters of the AGC system.

Moreover, it is also used to indicate the unit response capability of thermal power plants and DCHP units in power balancing control. For the N-1 analysis, the power deviation at the Danish – German border as the simulation output is again used to indicate the sensitivity to the input parameters of the dynamic model. In this chapter, the sensitivity analysis is used to indicate the critical inputs that are responsible for a drastic change in the outputs with regard to the regulating power control capability of the power generating units. The sensitivities of the outputs with respect to input parameters such as ramp rate, boiler time constant, and *pf* of AGC system, are analyzed. By running the power system model using simulation study cases and changing one input parameter at a time, the sensitivity of the deviation from planned power exchange is illustrated.

## 7.3 Dynamic sensitivity analysis of thermal power plants

The centralized thermal power plants in the western Danish power system, so called Energinet.dk-west (ENDK-west) are separated into 4 groups based on their characteristics of boiler time constant in the thermal boiler and ramp rate limiter in the boiler turbine control, as already described in chapter 4. A comparison of the units' responses from four centralized thermal power plants with the different ramp rate capability and different units' time response within 4 operational ranges, as shown in Table 7-1, have been carried out.

**TABLE 7-1**
**RAMP RATE LIMITER AND TIME RESPONSE OF POWER PLANTS IN WESTERN DENMARK**

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (sec.) |
|---|---|---|---|---|---|---|
| Plant 1 | 400 | 2 | 2 | 4 | 2 | 180 |
| Plant 2 | 400 | 1.5 | 2 | 4 | 2 | 180 |
| Plant 3 | 400 | 2 | 2 | 8 | 2 | 180 |
| Plant 4 | 400 | 2 | 2 | 4 | 2 | 300 |

The units' responses due to a load step for the 4 centralized power plants with different ramp rate capability and different boiler time constant within the operational ranges of < 35% is illustrated in Figure 7-1. The units' responses within operation range of 35% - 50%, 50% - 90%, and > 90% can also be observed in Figure 7-3, Figure 7-5 and Figure 7-7 respectively. A comparison of the units' responses for the 4 centralized power plants due to a load step within the operational range of 30% - 95% is illustrated in Figure 7-9.

In Figure 7-1, a load step of 5% is introduced at t = 600 sec. for the operational range of < 35%. It can be seen that the units' responses are influenced by ramp rate and boiler time constant. Figure 7-2 shows the ramp rate response ($L_R$) in the boiler turbine control and the influence of the thermal dynamic boiler ($P_t$) due to the boiler time constant. The boiler turbine control model and the thermal boiler model are illustrated in Figure 4-3 and Figure 4-4 respectively. It can be observed that a power plant unit 4 gives the slowest response due to its boiler time constant. It can also be seen that a power plant unit 2 gives a faster response than the plant unit 4; even though the plant unit 2 has a lower ramp rate. A power plant unit 1 and a power plant unit 3, which have the same values of ramp rate and boiler time constant in this operation range, give the same response.

In Figure 7-3, a load step of 5% is again introduced at t = 600 sec. for the operational range of 35% - 50%. It can be observed that the response of a plant unit 4 is mainly influenced by the boiler time constant of the thermal boiler. All the other power plants, which have the same ramp rate and boiler time constant in this operational range as shown in Figure 7-4, give the same response. A significant influence in the units' responses due to the boiler time constants in this operational range can be observed. Figure 7-5 shows the units' responses in the operation range of 50% - 90% when a load step of 5% in introduced at t = 600 sec. It can be seen that a power plant unit 3, with the highest ramp rate, gives the fastest response and a power plant unit 4, with the largest boiler time constant, gives the slowest response, even though it has the same ramp rate as power plant unit 1 and power plant unit 2, as illustrated in Figure 7-6. However, it can be observed that the units' responses of power plant unit 1, unit 2 and unit 3, which have the same boiler time constant, are not much different in this small load step, even though the ramp rate of the unit 3 is 2 times larger than the others.

Figure 7-7 shows the units' responses in the operation range of >90% when a load step of 5% is again introduced at t = 600 sec. In this operational range, all power plants have the same ramp rate of 2% per minute as shown in Figure 7-8. It can be seen that a power plant unit 4, again, gives the slowest response due to its boiler time constant. Figure 7-9 shows the units' responses of the thermal power plants in the operational range of 30% - 95% when a large load step is introduced at t = 360 sec. A comparison of the units' responses can be made. It can be seen that a power plant unit 3, with the highest ramp rate, gives the fastest response and a power plant unit 4, with the largest boiler time constant, gives the slowest response. A power plant unit 1 gives a faster response than a plant unit 2 due to its higher ramp rate in the operational range of < 35%.

It can be observed that the response of a power plant unit 3 is much faster than the other plants due to the fast ramp rate, in the operational range of 50% - 90%, as shown in Figure 7-10. It can also be indicated that the unit response for long-term dynamic simulation is mainly determined by the ramp rate limiter component in the boiler turbine control model and also strongly influenced by the dynamic behaviour of the boiler time constant, while other components in the thermal power plant model, such as the speed governor and the generic steam turbine are used for improving the real response and for maintaining the physical components of the conventional power plant.

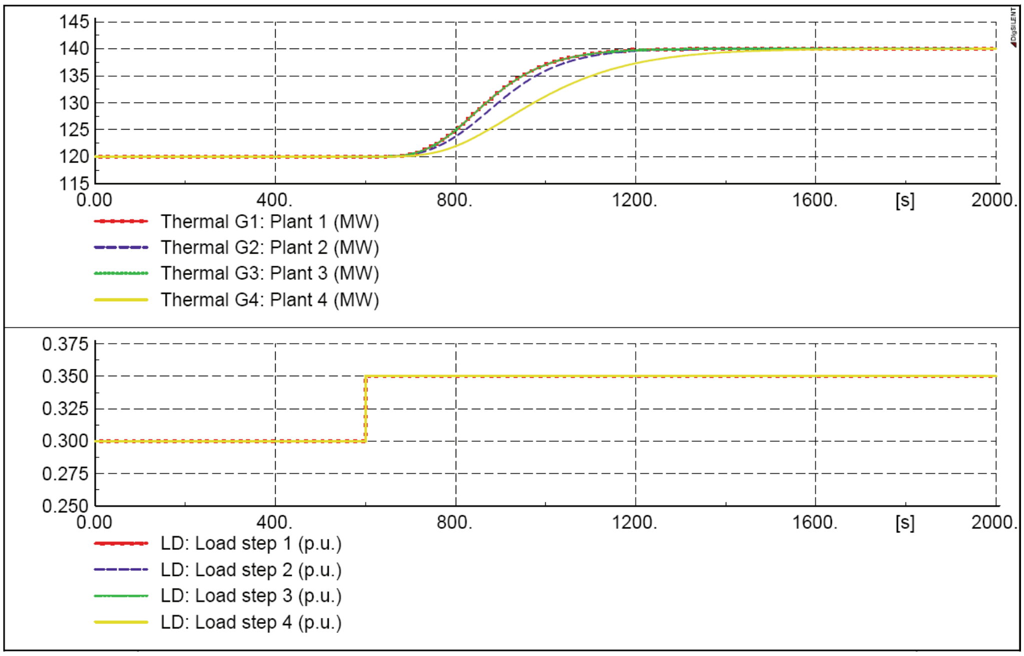


**Figure 7-1. Comparison of responses from 4 centralized power plants with different ramp rate and boiler time constant in operational range of < 35%**

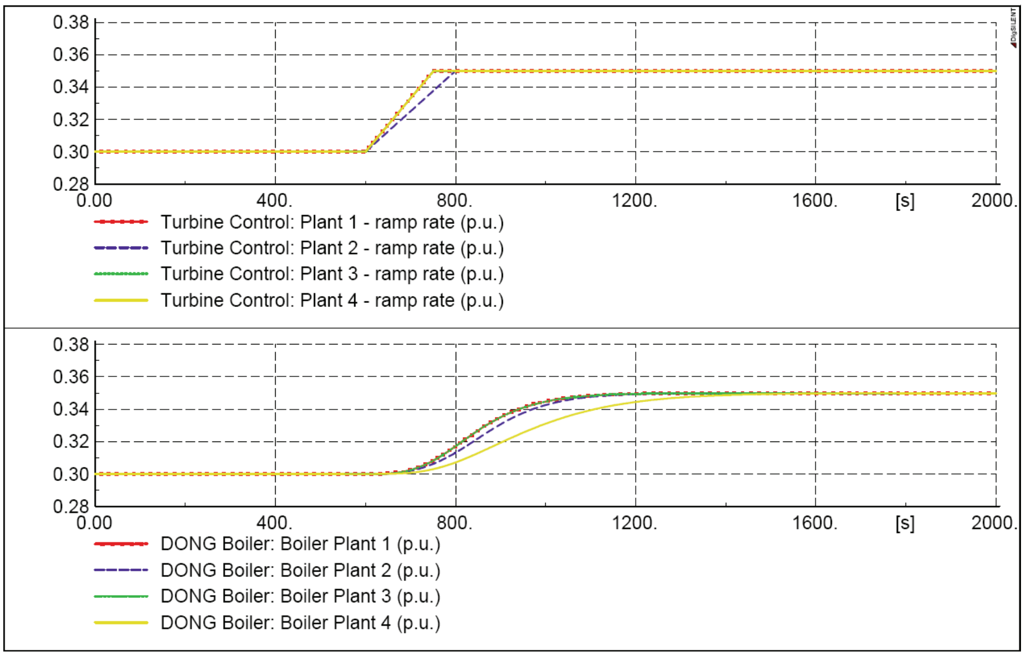


**Figure 7-2. Comparison of ramp rate responses (above) and dynamic boiler responses (below) from 4 centralized power plants in operational range of < 35%**

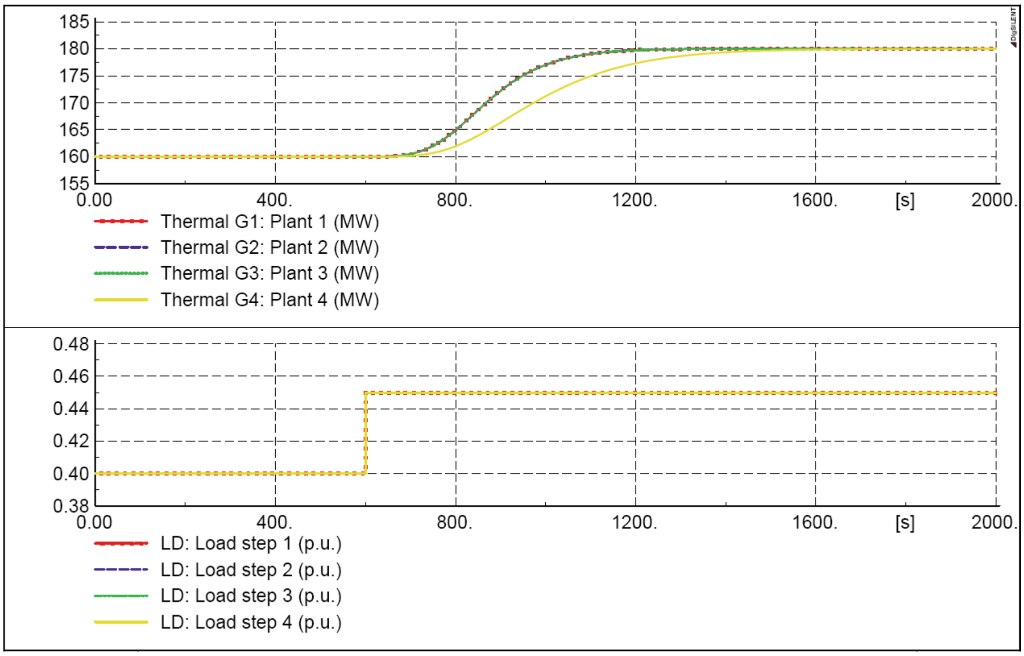


**Figure 7-3. Comparison of responses from 4 centralized power plants with different ramp rate and boiler time constant in operational range of 35% - 50%**

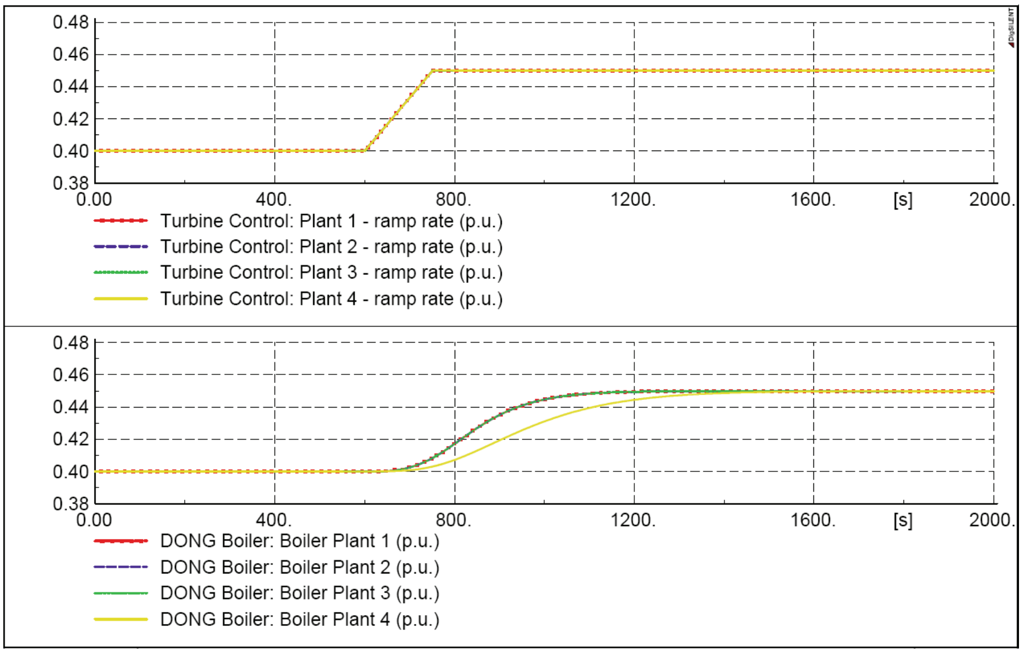


**Figure 7-4. Comparison of ramp rate responses (above) and dynamic boiler responses (below) from 4 centralized power plants in operational range of 35% - 50%**

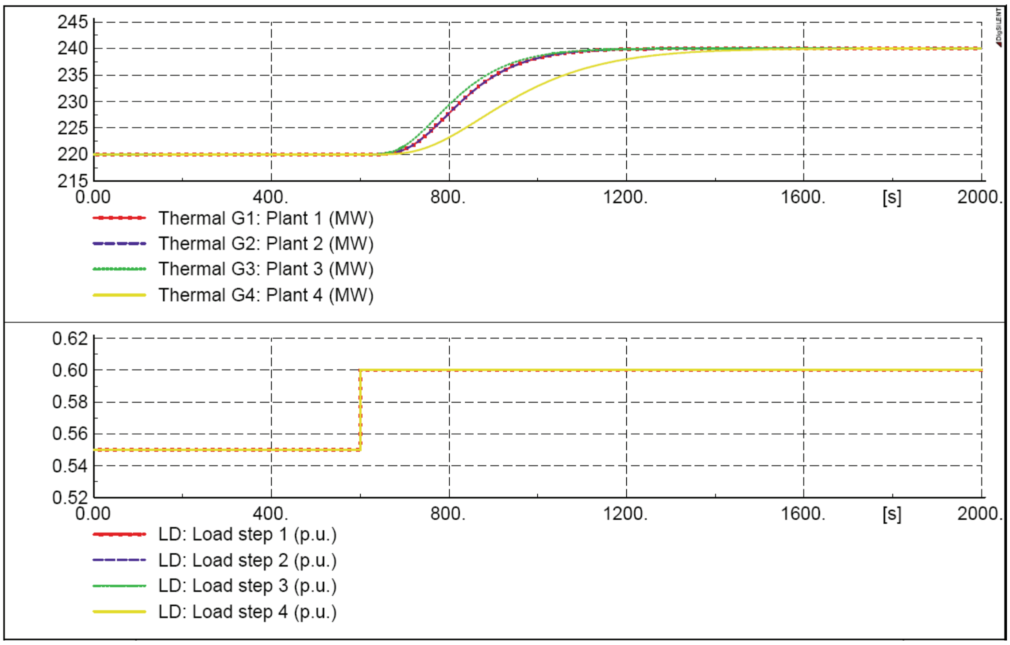


**Figure 7-5. Comparison of responses from 4 centralized power plants with different ramp rate and boiler time constant in operational range of 50% - 90%**

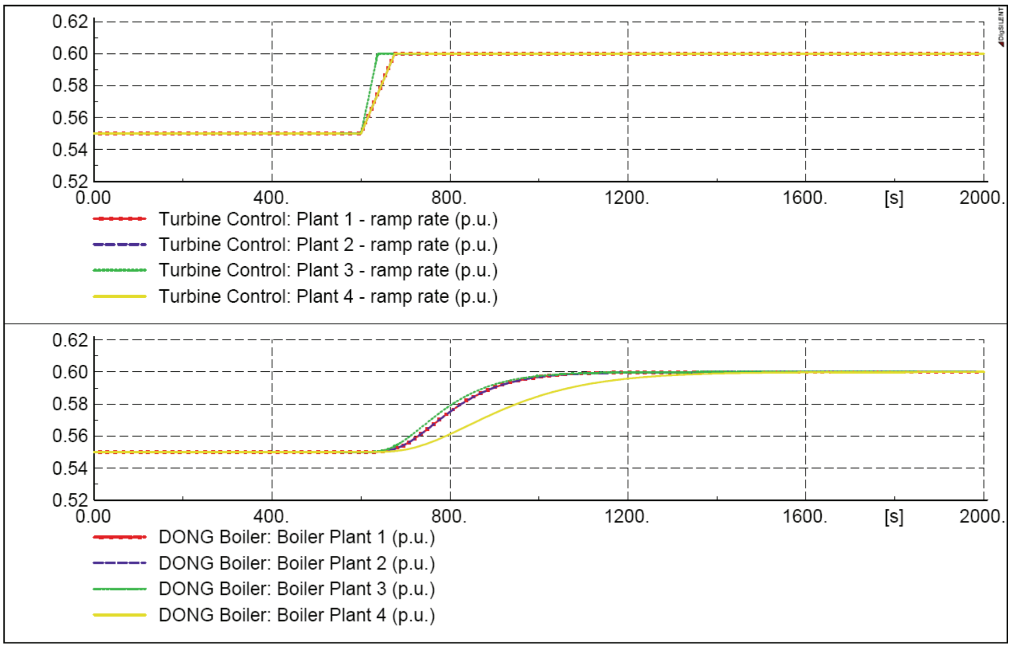


**Figure 7-6. Comparison of ramp rate responses (above) and dynamic boiler responses (below) from 4 centralized power plants in operational range of 50% - 90%**

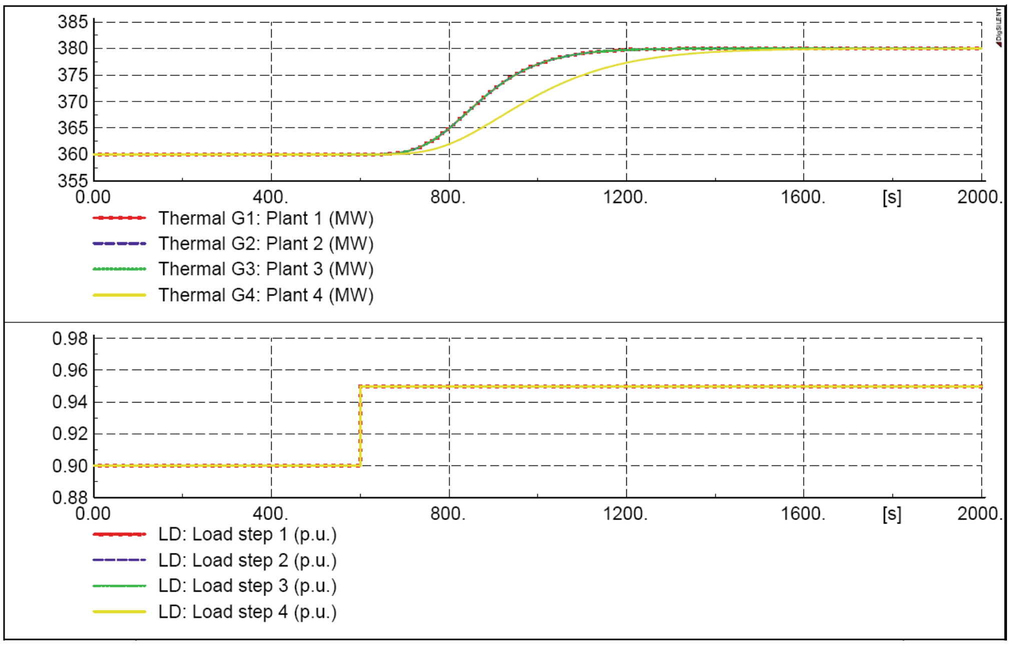


**Figure 7-7. Comparison of responses from 4 centralized power plants with different ramp rate and boiler time constant in operational range of > 90%**

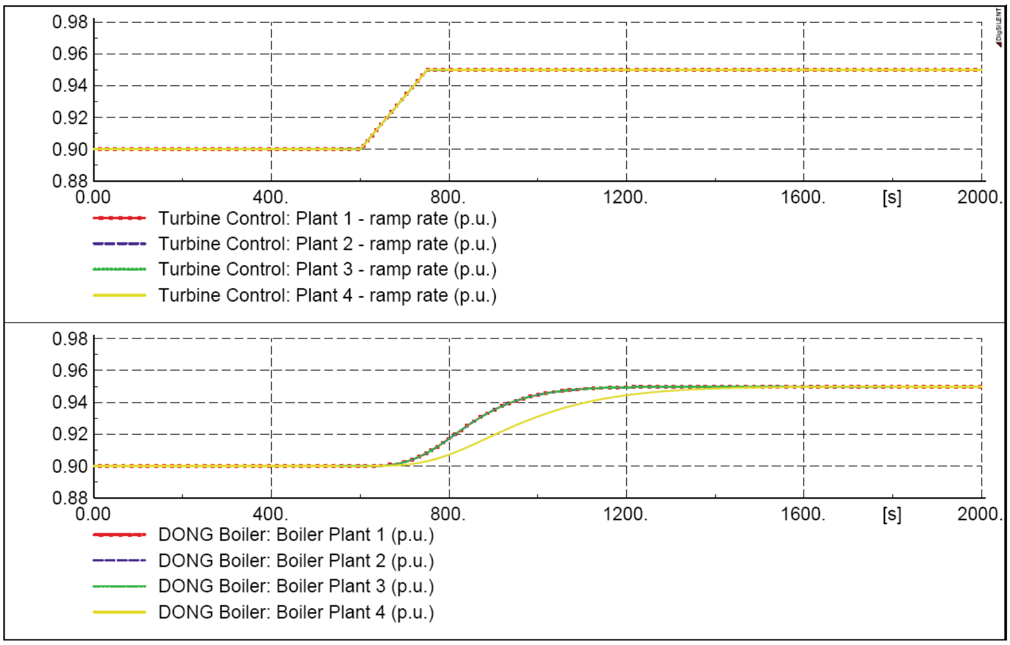


**Figure 7-8. Comparison of ramp rate responses (above) and dynamic boiler responses (below) from 4 centralized power plants in operational range of > 90%**

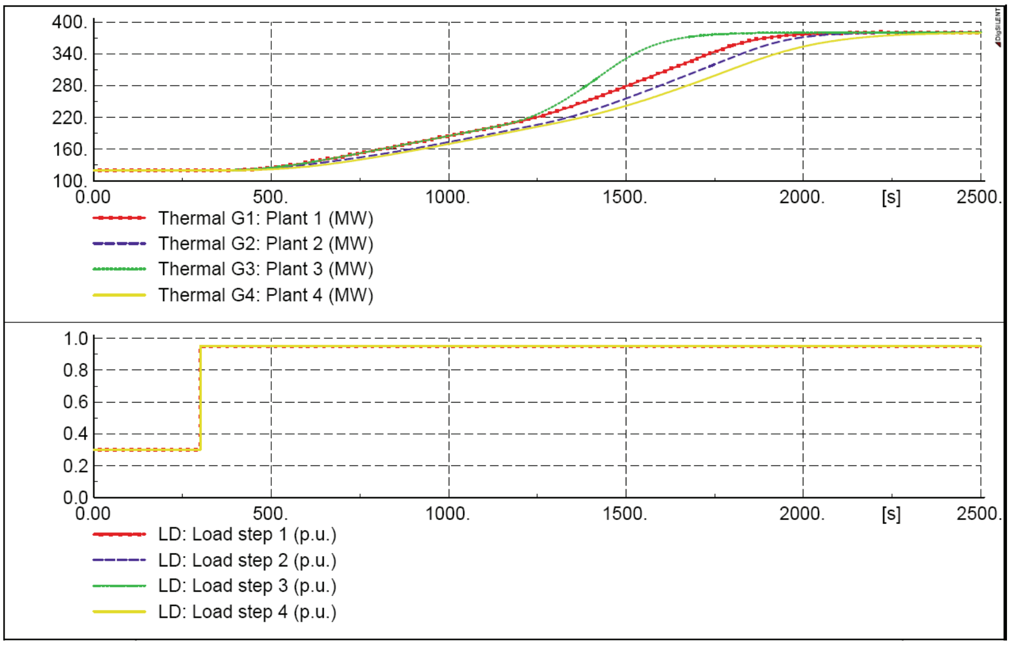


**Figure 7-9. Comparison of responses from 4 centralized power plants with different ramp rate and boiler time constant at operation range 30% - 95%**

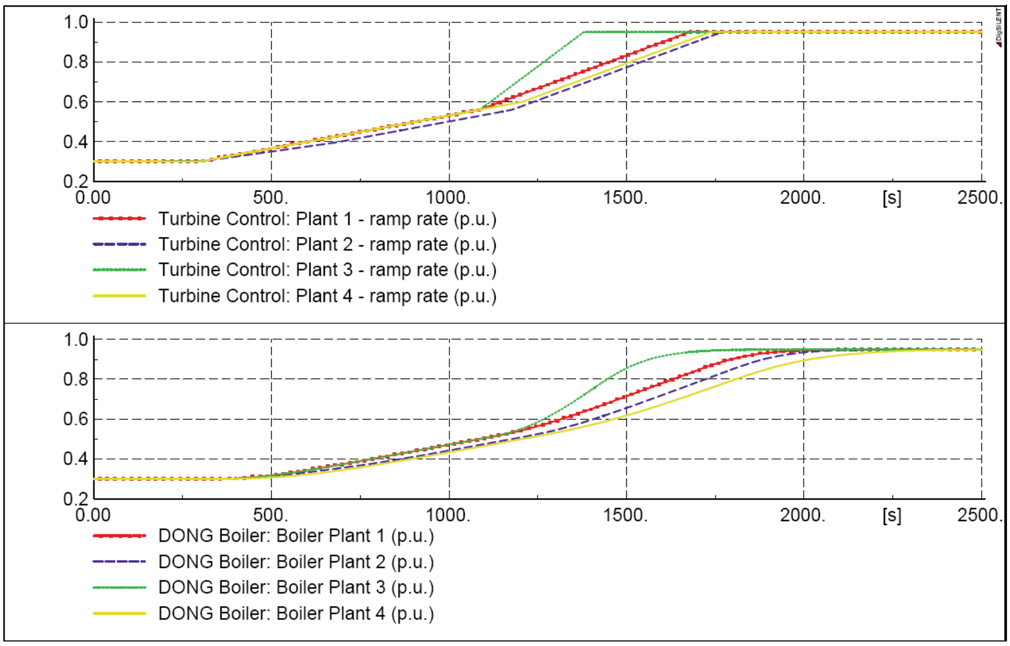


**Figure 7-10. Comparison of ramp rate responses (above) and dynamic boiler responses (below) from 4 centralized power plants in operational range of 30% - 95%**

## 7.4 Dynamic sensitivity analysis of power system operations

In this section, a dynamic sensitivity analysis on the control parameters of the AGC system is presented. Dynamic simulation studies in power system operations have been carried out with different chosen *pf* values for the fast and slow units as shown in Table 7-2. In this project, the *pf* value for each power plant can be varied from 0.0 to 1.0. The summation of the *pf* values of all power generating units in the AGC system should have a maximum of one as described in chapter 3.

Dynamic sensitivity analyses on the power system operation with different system control scenarios have been carried out using the following case studies:

- Different share of centralized thermal power plants
- Different share of decentralized power generating units
- N-1 analysis

First, the control parameters of the AGC system, which influenced the centralized power plants units' responses with regard to power balancing control, are analyzed. Second, the control parameters of the AGC system, which influence the DCHP units' responses with regard to power balancing control, are analysed and the performance of the DCHP units is demonstrated. Third, an N-1 analysis is carried out to investigate the systems ability to withstand the loss of any single component, in this study; a centralized thermal power plant is taken out of service. This analysis focuses on the capability of the generating units to keep the power deviation at the Danish-German border within an acceptable limit.

TABLE 7-2
PARTICIPATION FACTORS USED IN SIMULATION STUDIES

| Power Plants | Active Power (MW) | Ramp <35% (%/min.) | Ramp 35-50% (%/min.) | Ramp 50-90% (%/min.) | Ramp 90-100% (%/min.) | Time response (sec.) | Participation factor (pf) |
|---|---|---|---|---|---|---|---|
| **Plant 1** | 1684 | 2 | 2 | 4 | 2 | 210 | 0.0 – 1.0 |
| **Plant 2** | 700 | 1.5 | 2 | 4 | 2 | 210 | 0.0 – 1.0 |
| **Plant 3** | 392 | 2 | 2 | 8 | 2 | 210 | 0.0 – 1.0 |
| **Plant 4** | 625 | 2 | 2 | 4 | 2 | 330 | 0.0 – 1.0 |

### 7.4.1 Different share of centralized thermal power plants

In this section, a simulation study for different share among the centralized thermal power plants with regard to power balancing control is carried out. The main part of this section is devoted to the simulation study of the behaviour of the thermal power plants in a long-term dynamic simulation. Time series data of DCHP unit generation is used, as the decentralized CHP units are assumed to be operated according to their operational plan. In this study, the deviation from the planned power exchange at the Danish – German border is used to indicate the power balancing control capability of the thermal power plants.

Simulation studies are presented in 5 cases as shown in Table 7-3. Figure 7-11 shows the comparison of the deviations from planned power exchange with the UCTE system when one of the selected centralized power plant is operated with *pf* value = 0.4 and other power plants are operated with *pf* = 0.2. Detailed simulation result during 26,000 sec. to 35,000 sec. is illustrated in Figure 7-12. In case 1, all power plants are operated with *pf* = 0.25 as a based case. Various cases are investigated in which each of these power plants are operated with *pf* = 0.4. The power productions generated from each centralized power plants in case 1 to case 5 are shown in Figure 7-13 to Figure 7-17. The total power generations from the centralized power plants and the DCHP units are illustrated in Figure 7-18. Data time series of the power exchange with the Nordel system and loads, and wind power generations in case 1 to case 5 which are used as input to the model are shown in Figure 7-19 and Figure 7-20 respectively.

Figure 7-12 shows the deviation from the planned power exchange when the power plants are operated according to the *pf* values in Table 7-3. It can be seen that the deviation is kept to the minimum when a power plant unit 3 is operated with *pf* = 0.4 in case 4. The largest deviation can be observed when a plant unit 4 is operated with *pf* = 0.4 in case 5. However, the power deviations of case 1 to case 5 are not much different. In Figure 7-13, Figure 7-14, Figure 7-15, Figure 7-16, and Figure 7-17, it can be seen that the chosen *pf* values in AGC system give a significant influence to the units' responses. Figure 7-18 shows the comparison of the total power production from the centralized thermal power plants in case 1 to case 5. It can be seen that the total generation from the thermal power plants in each case are almost the same.

TABLE 7-3
CASE STUDIES WITH DIFFERENT SHARE AMONG CENTRALIZED POWER PLANTS

| Power Plants | Active Power (MW) | Case 1 pf value | Case 2 pf value | Case 3 pf value | Case 4 pf value | Case 5 pf value |
|---|---|---|---|---|---|---|
| **Plant 1** | 1684 | 0.25 | **0.4** | 0.2 | 0.2 | 0.2 |
| **Plant 2** | 700 | 0.25 | 0.2 | **0.4** | 0.2 | 0.2 |
| **Plant 3** | 392 | 0.25 | 0.2 | 0.2 | **0.4** | 0.2 |
| **Plant 4** | 625 | 0.25 | 0.2 | 0.2 | 0.2 | **0.4** |

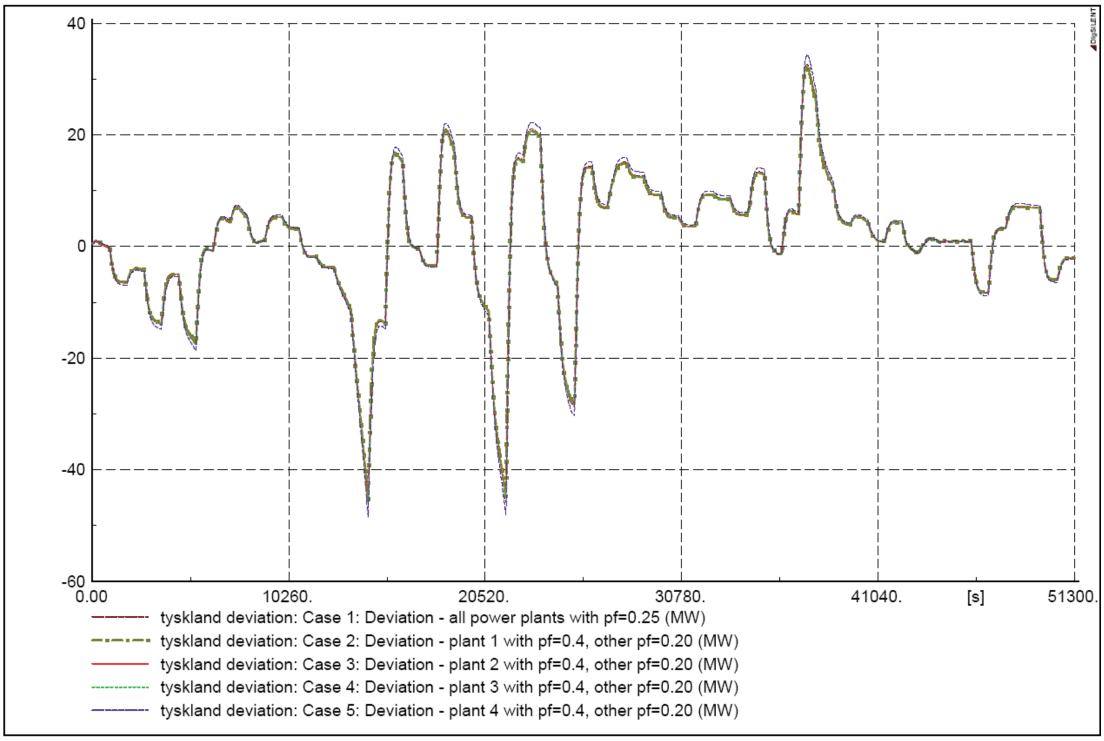


**Figure 7-11. Deviation from planned power exchange with the UCTE system**

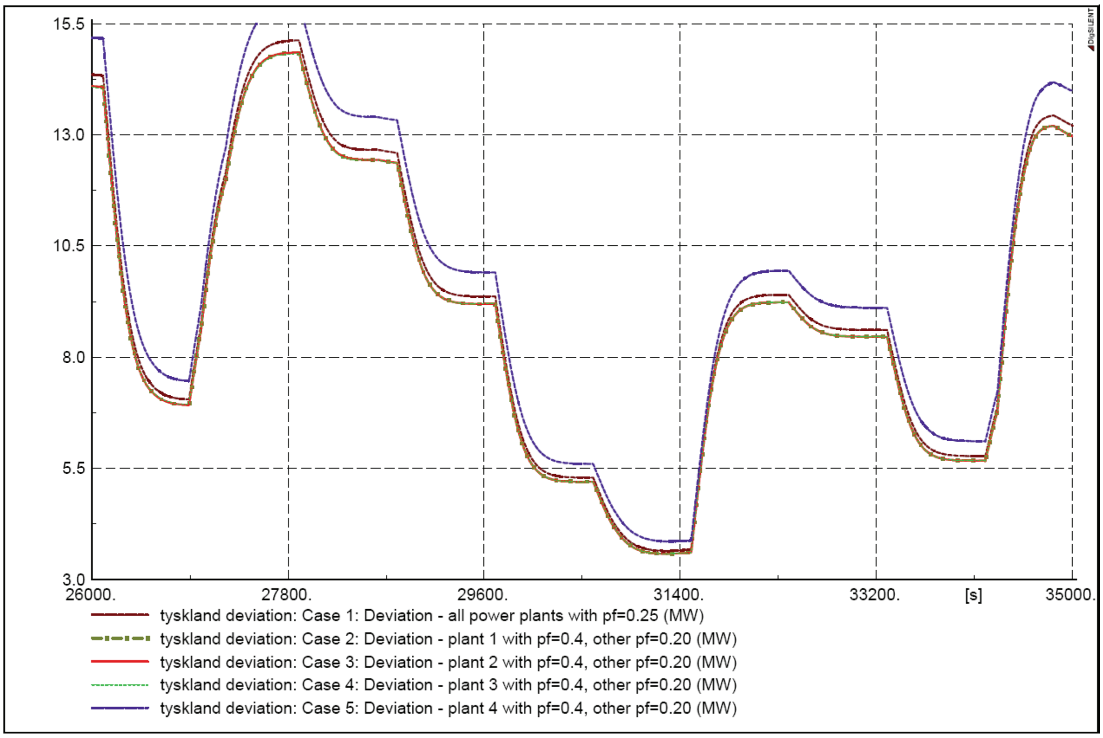


**Figure 7-12. Deviation from planned power exchange with UCTE at 26,000 sec. – 35,000 sec.**

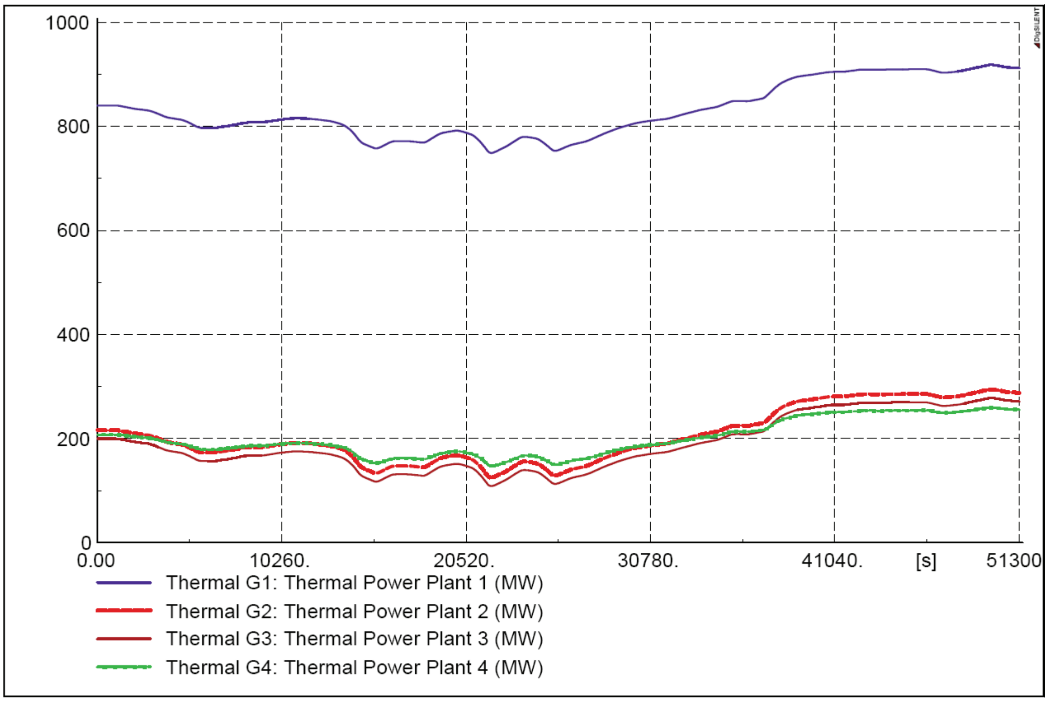


**Figure 7-13. Power generations from power plants in case 1**

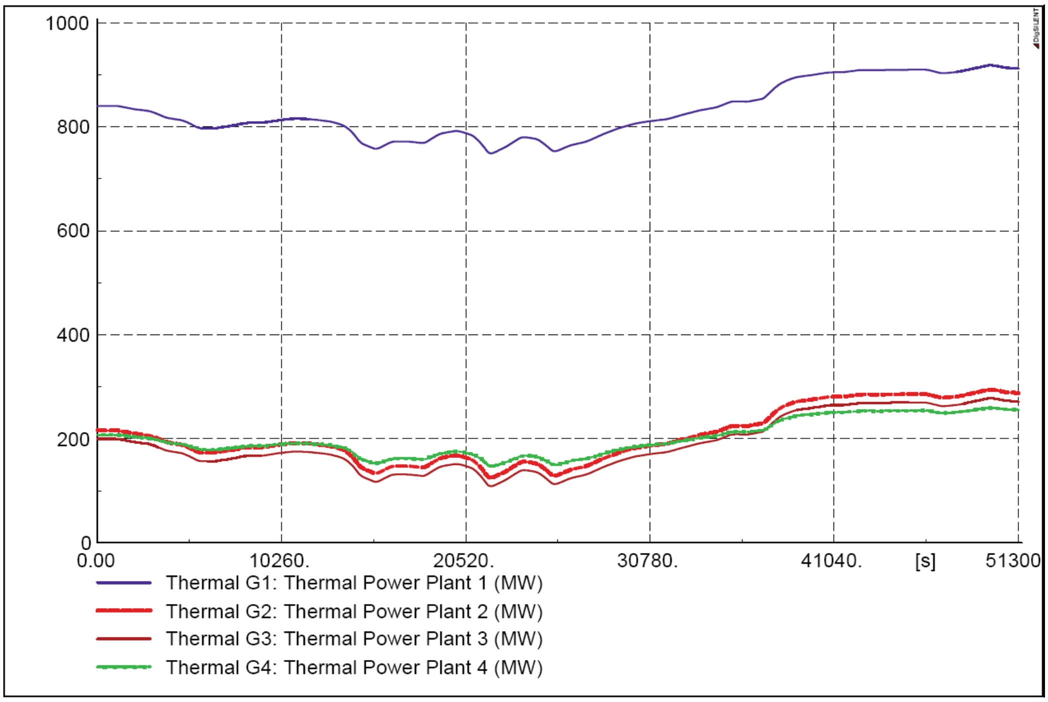


**Figure 7-14. Power generations from power plants in case 2**

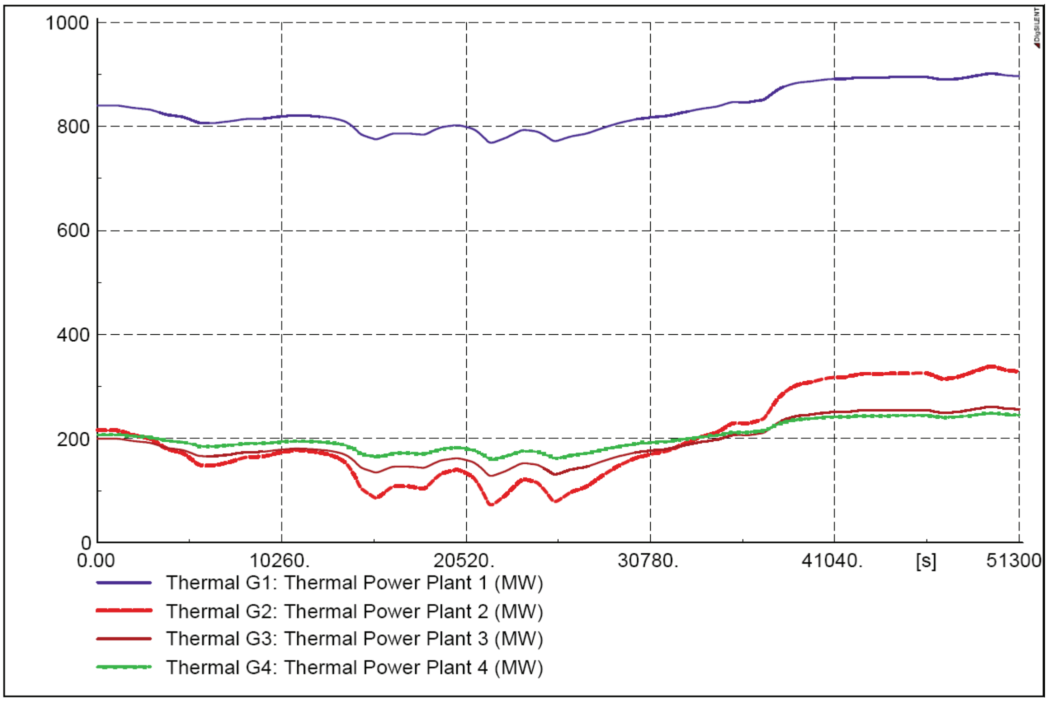


**Figure 7-15. Power generations from power plants in case 3**

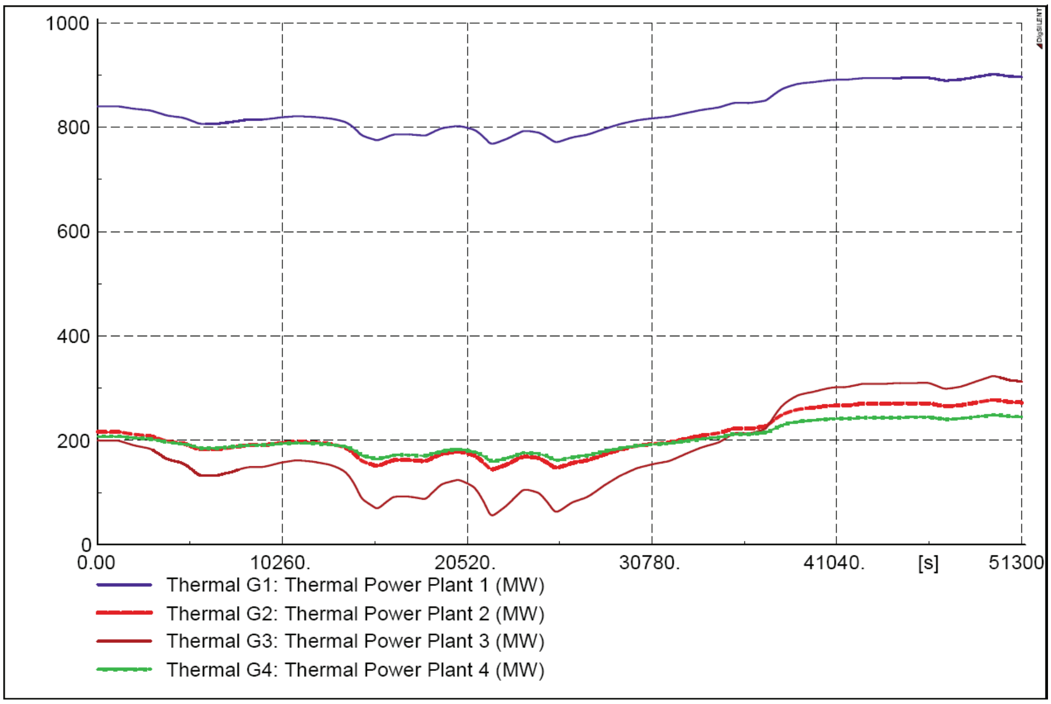


**Figure 7-16. Power generations from power plants in case 4**

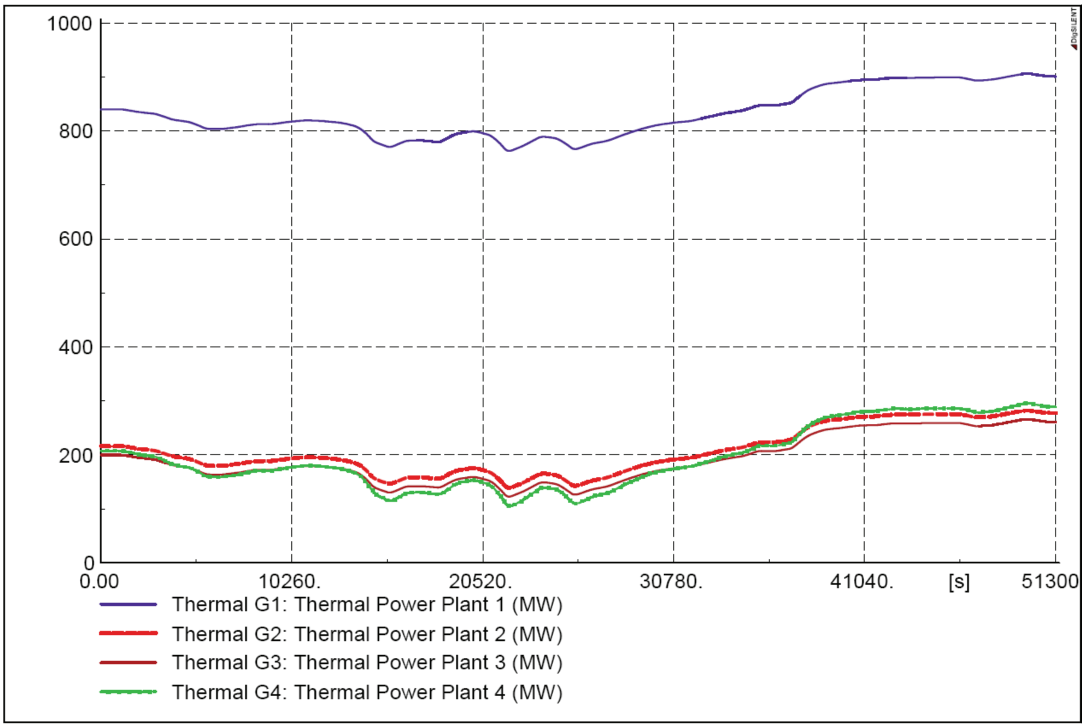


**Figure 7-17. Power generations from power plants in case 5**

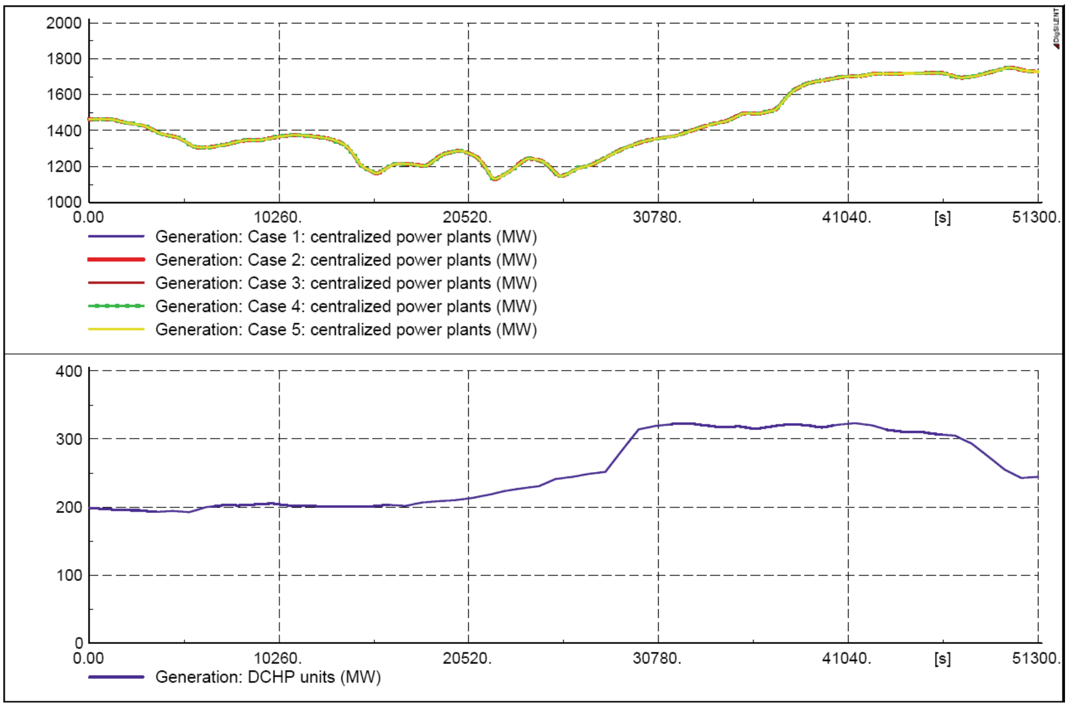


**Figure 7-18. Total power generations from centralized power plants in case 1 to case 5 (above) and power generation from DCHP units (below) [10]**

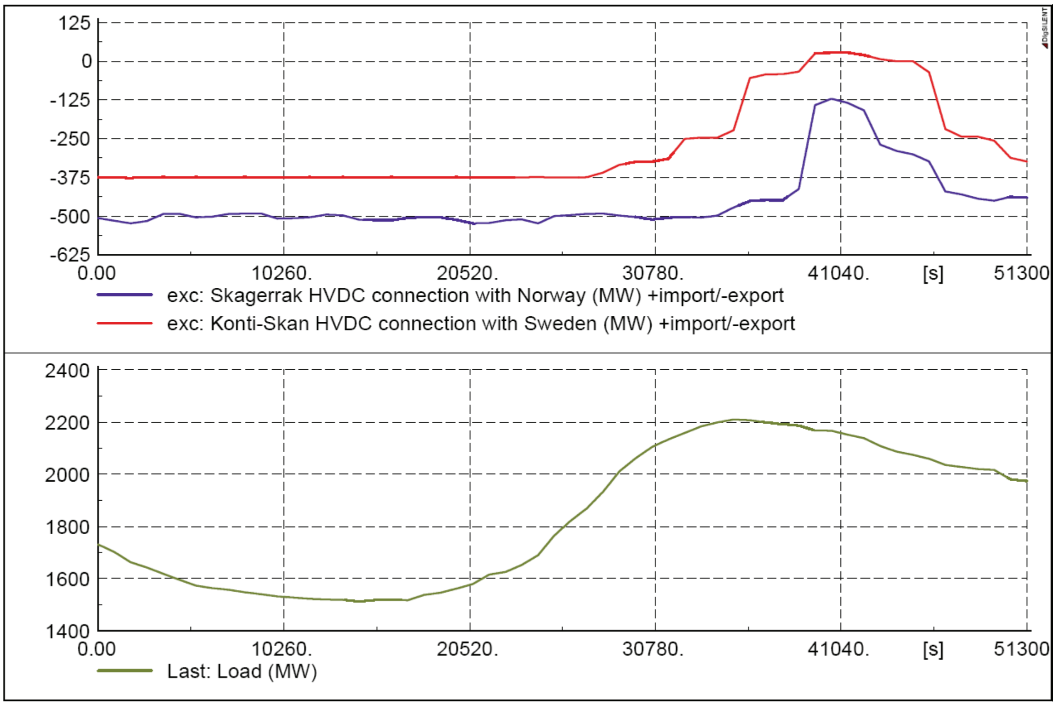


**Figure 7-19. Power transaction with the Nordel system (above) and load (below) [10]**

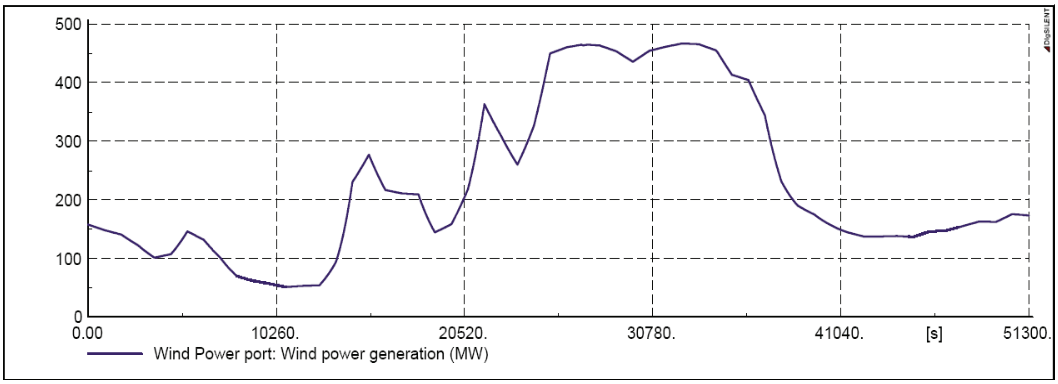


**Figure 7-20. Wind power generation**

From this simulation study, it can be seen that the responses from thermal power plants are influenced by the *pf* values appointed from the AGC system. The chosen *pf* in AGC system give a significant influence in the units' response with regard to the power balancing control. Simulation results of the wind power generations from on-land wind turbines, HRA wind farm and HRB wind farm are illustrated in Appendix C.

### 7.4.2 Different share of DCHP units

In this section, a simulation study for different shares of DCHP units is carried out. The main part of this section is devoted to the simulation study of centralized power plants and DCHP units for long-term dynamic simulation. The decentralized CHP units are operated by the AGC system.

Table 7-4 shows 5 study cases which have been carried out, the chosen *pf* values for the DCHP units are varied from 0 to 0.20, with regard to the limit capacities of the DCHP unit as shown in Figure 7-23. In this simulation study, the deviation from the planned power exchange is, again, used to indicate the power balancing control capability of the DCHP units with different *pf* values in the AGC system. The deviations from planned power exchange with the UCTE system in case 1 to case 5 are illustrated in Figure 7-21. Power productions generated from the centralized power plants in case 1 to case 5 are illustrated in Figure 7-22. Power generation from each centralized power plants in case 1 to case 5 are shown in Appendix C. Power productions from the DCHP units in case 1 to case 5 are illustrated in Figure 7-23. A data time series of the power transaction with the Nordel system and the loads, and the wind power generation in case 1 to case 5 are the same as shown in Figure 7-19 and Figure 7-20 respectively.

From Figure 7-21, it can be observed that the deviation from planned power exchange is kept to the minimum when the DCHP units are operated with the highest *pf* value in case 5. However, the largest deviation can be seen in the same study case, when the DCHP units are operated at their maximum capacity during t = 29000 sec. to t = 42000 sec. as shown in Figure 7-23. The chosen participation factor for the centralized power plants is decreased, when the participation factor for the DCHP unit is increased, as shown in Table 7-4. Therefore, the deviations in case 2 to case 5 are higher than case 1, during t = 29000 sec. to t = 42000 sec. due to the regulating power provided from centralized power plants is based on participation factor from the AGC system.

TABLE 7-4
CASE STUDIES IN DIFFERENT SHARE OF DCHP UNITS

| Power Plants | Active Power (MW) | Case 1 pf value | Case 2 pf value | Case 3 pf value | Case 4 pf value | Case 5 pf value |
|---|---|---|---|---|---|---|
| **Plant 1** | 1684 | 0.25 | 0.2375 | 0.225 | 0.2125 | 0.2 |
| **Plant 2** | 700 | 0.25 | 0.2375 | 0.225 | 0.2125 | 0.2 |
| **Plant 3** | 392 | 0.25 | 0.2375 | 0.225 | 0.2125 | 0.2 |
| **Plant 4** | 625 | 0.25 | 0.2375 | 0.225 | 0.2125 | 0.2 |
| **DCHP** | 400 | **0** | **0.05** | **0.1** | **0.15** | **0.2** |

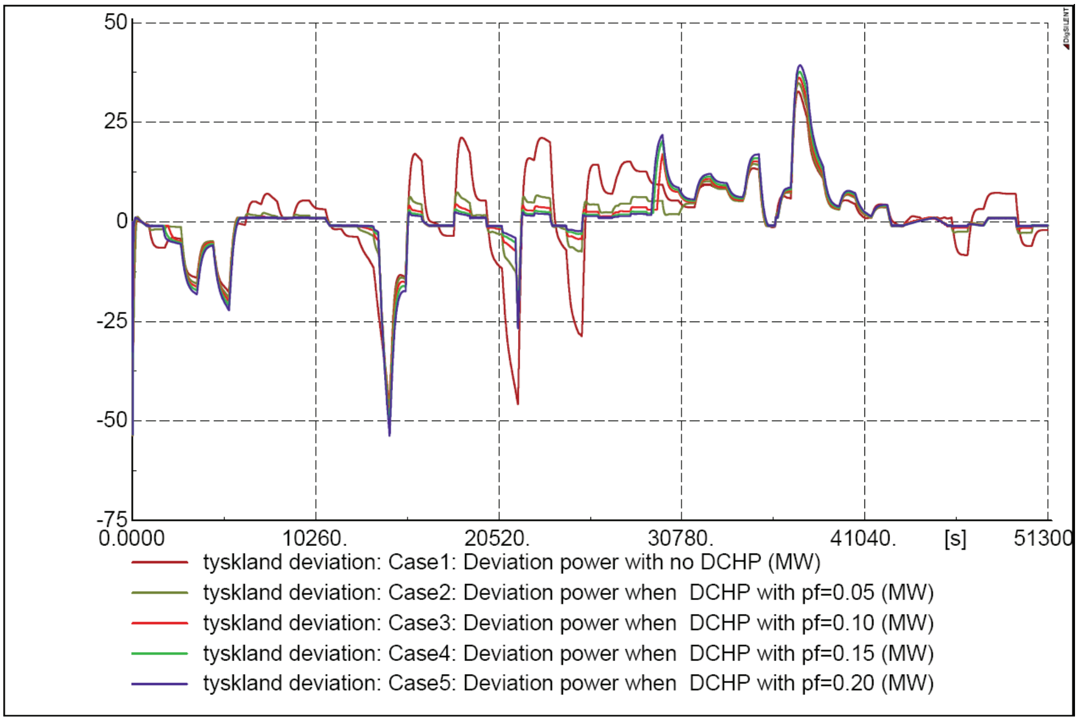


**Figure 7-21. Deviation from planned power exchange with UCTE**

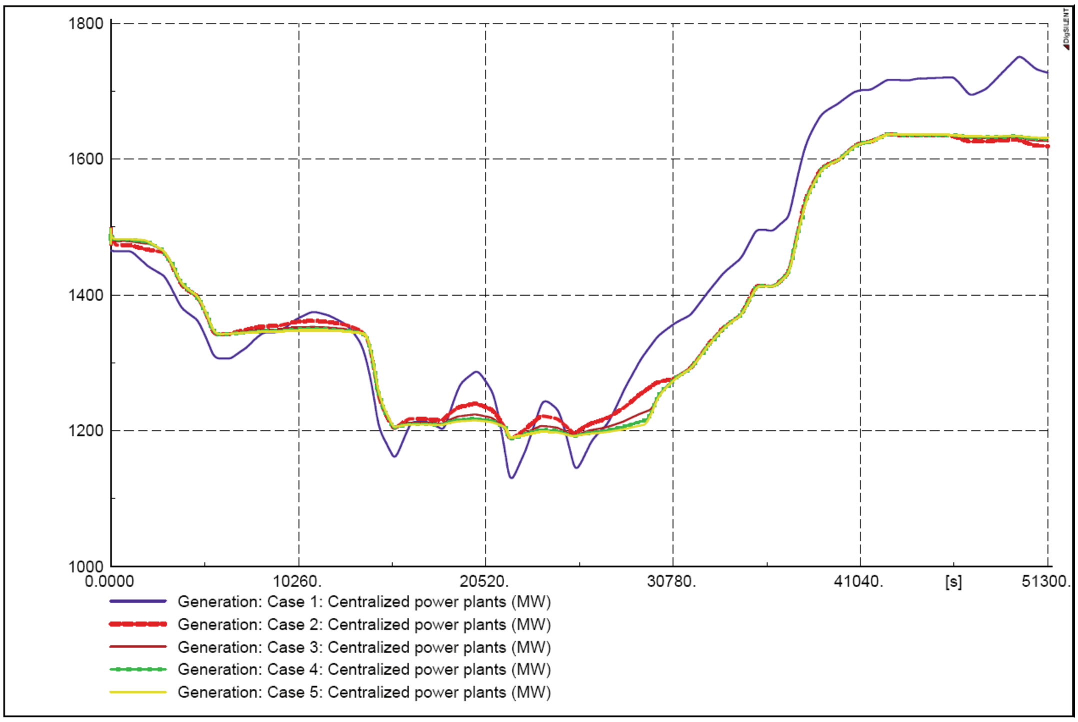


**Figure 7-22. Power generations from centralized power plants in case 1 to case 5**

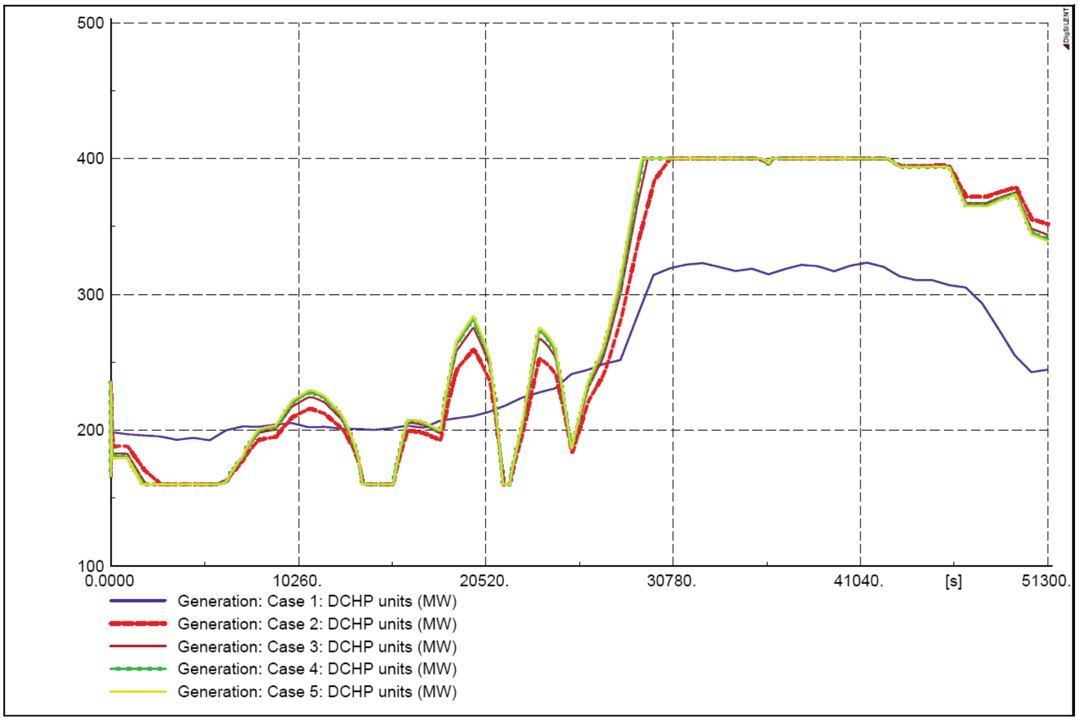


**Figure 7-23. Power productions from DCHP units in case 1 to case 5**

From this simulation study, it can be observed that the DCHP units' responses are influenced by the chosen *pf* values of the AGC system. It can also be seen that the fast secondary control of the DCHP units give a very good performance for minimizing the power deviation. However, the DCHP units' capacity should be taken into account when planning the power balancing control strategy. It can be expected that the performance of power balancing control in the Danish power system can be improved with an increase of DCHP generation capacities which work in cooperation with the AGC system.

### 7.4.3 N-1 analysis

In this section, the simulation study for N-1 analysis is carried out. N-1 analysis is carried out to investigate the capability of the system to be able to withstand the loss of any single component, in this case, a centralized thermal power plant. The main part of this section is devoted to the simulation studies of N-1 analysis with regard to the power balancing control at the Danish – German border. The power deviation from the planned power exchange between Denmark and Germany are investigated. The time series data of the decentralized CHP units generation is used in this study as the DCHP units are assumed to operate based on tariff. Case studies are provided as shown in Table 7-5.

In study case 1, all power plants are operated with $pf = 0.25$, the simulation result is kept as a reference of a normal situation. N-1 analyses are carried out with the disconnection of a power plant unit 2, of a plant unit 3 and of a plant unit 4 in case 2, case 3, and case 4 respectively. The simulation studies have been carried out with the selected power plants due to the following reasons. The power plant unit 3 (Skærbærværket power plant) has the highest ramp rate capability. The power plant unit 4 (Enstedværket power plant) has the longest boiler time constant. The power plant unit 2 (Studstrup B3/B4) has the same ramp rate and boiler time constant as the other units in the system, in the operational range of 35% - 100%.

Power productions generated from each centralized power plant in case 1 to case 5 are illustrated in Figure 7-26 to Figure 7-29. The power productions from the DCHP units are shown in Figure 7-30. In this simulation study, the data time series of power transactions with the Nordel system and loads, and wind power generation in case 1 to case 5 are, again, the same as shown in Figure 7-19 and Figure 7-20 respectively. The deviations from planned power exchange with the UCTE system in study case 1 to case 4 are illustrated in Figure 7-24. The selected power plants is tripped from the system at t = 7200 sec. as illustrated in Figure 7-26. In this study, when the selected power plant is tripped from the system; the other power plants take over the control of the system. It can be seen that the power deviation exceed +/- 50 MW in all cases after the disconnection of the selected units. However, the deviations from planned power exchange with the UCTE system are brought back in the acceptable range of +/- 50 MW [42] within 500 sec. The capability of the secondary control from the available generating units, with regard to ramp rate and boiler time constant can be observed from Figure 7.26 to Figure 7.29.

TABLE 7-5
CASE STUDIES IN N-1 ANALYSIS

| Power Plants | Active Power (MW) | Case 1 pf value | Case 2 pf value | Case 3 pf value | Case 4 pf value |
|---|---|---|---|---|---|
| **Plant 1** | 1684 | 0.25 | 0.33 | 0.33 | 0.33 |
| **Plant 2** | 700 | 0.25 | - | 0.33 | 0.33 |
| **Plant 3** | 392 | 0.25 | 0.33 | - | 0.33 |
| **Plant 4** | 625 | 0.25 | 0.33 | 0.33 | - |

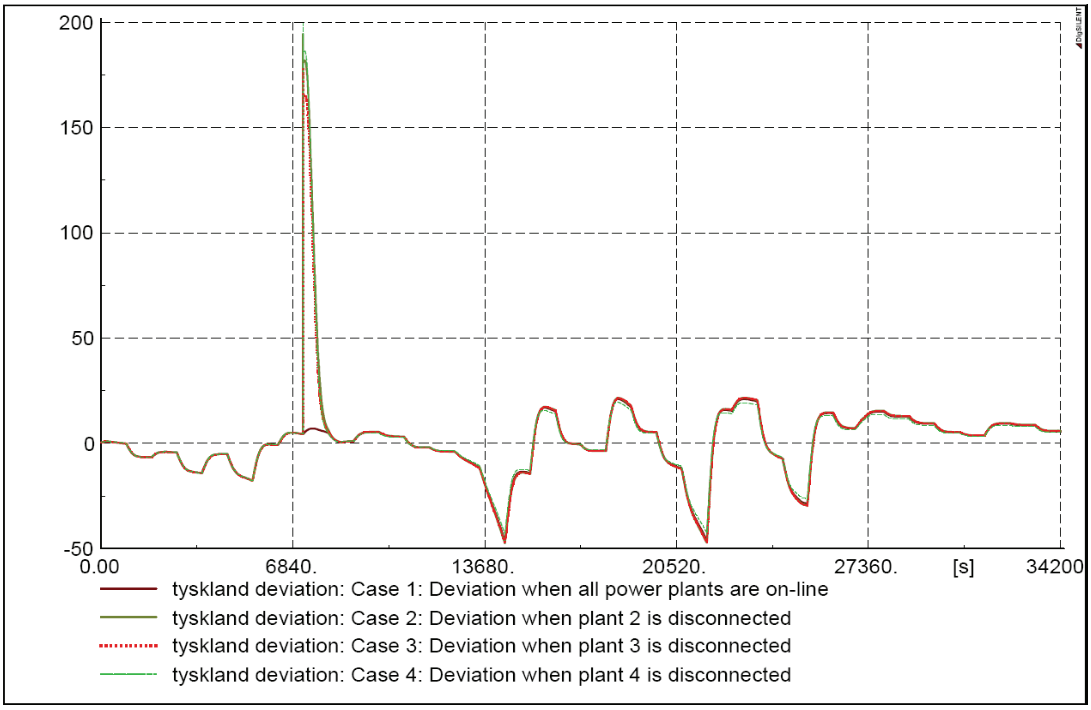


**Figure 7-24. Deviation from planned power exchange with UCTE**

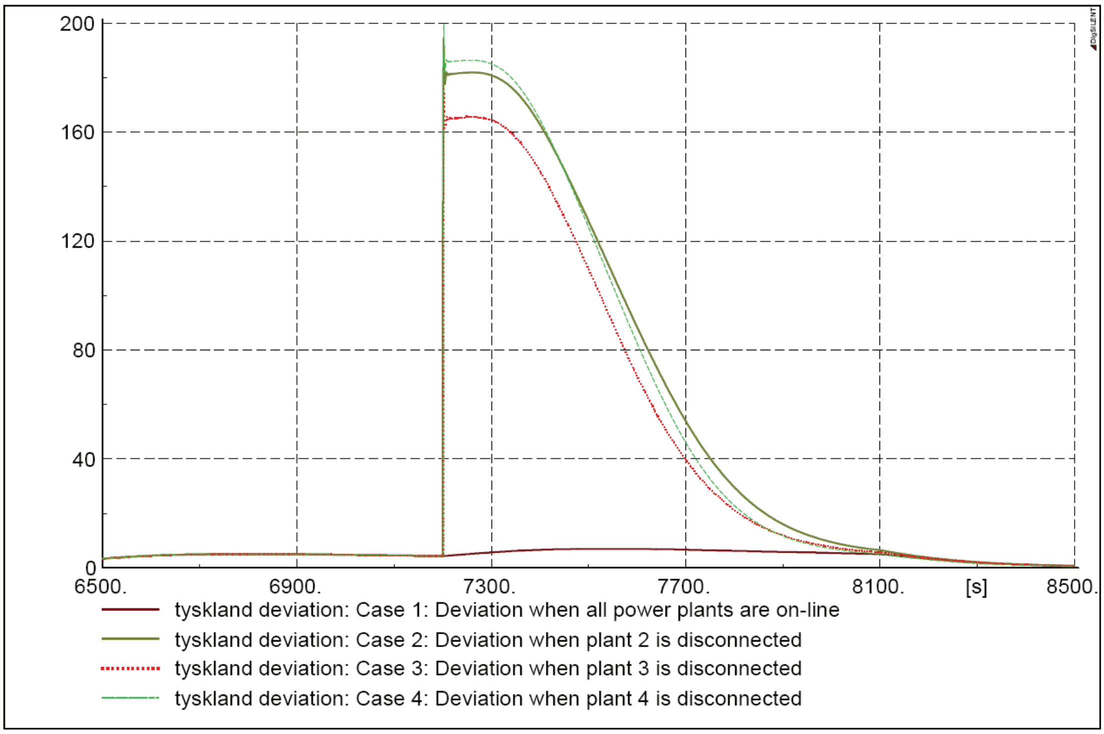


**Figure 7-25. Deviation from planned power exchange with UCTE during t = 6,500 sec. to t = 8500 sec.**

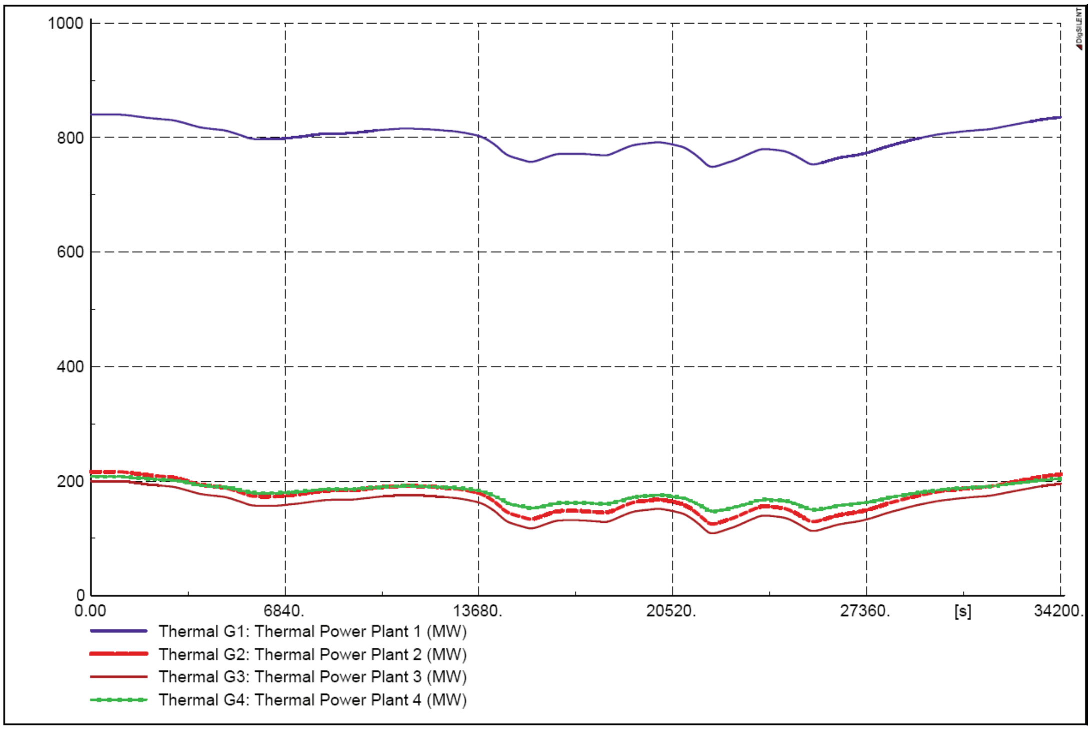


**Figure 7-26. Power production from centralized power plants in case 1**

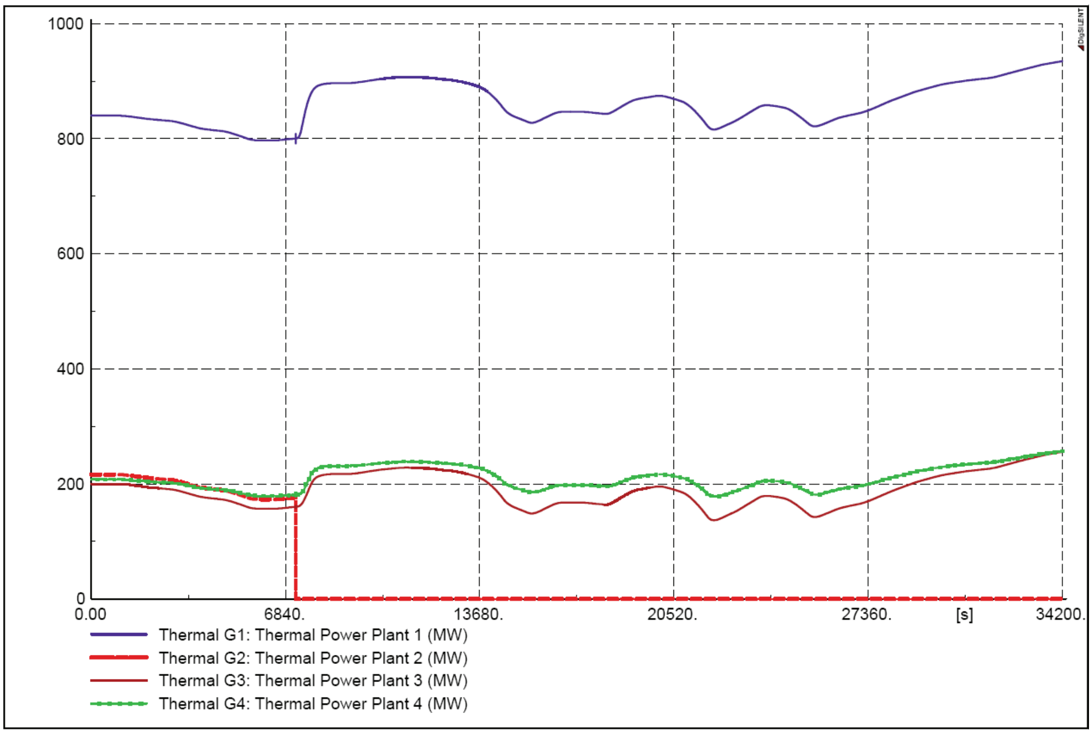


**Figure 7-27. Power production from centralized power plants in case 2**

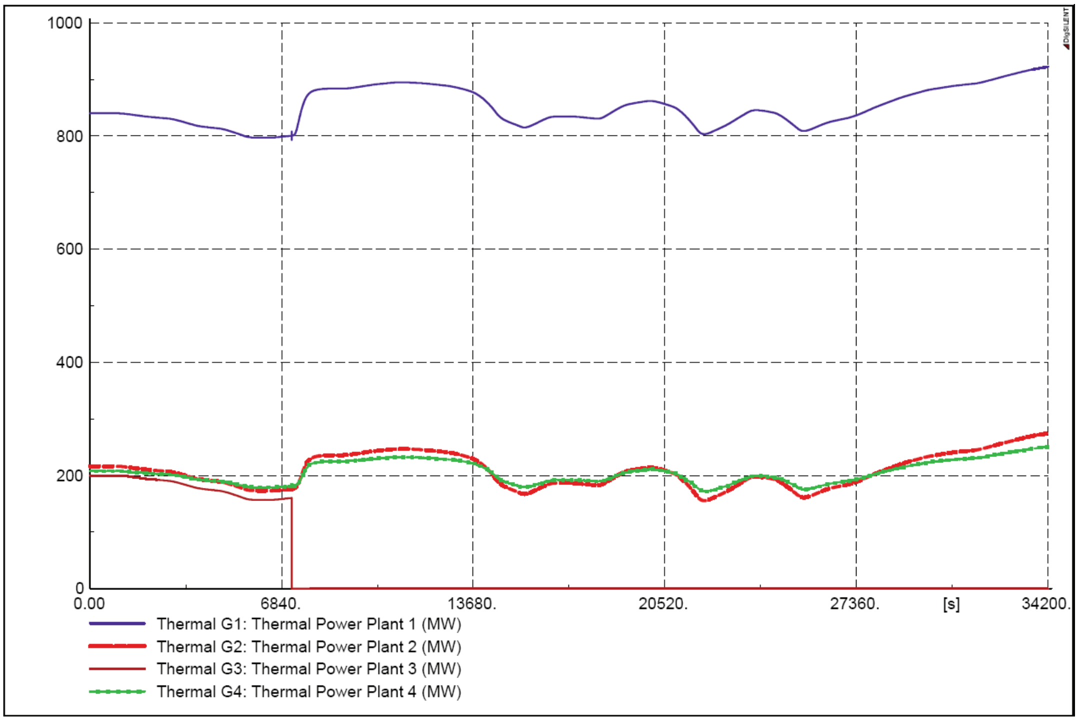


**Figure 7-28. Power production from centralized power plants in case 3**

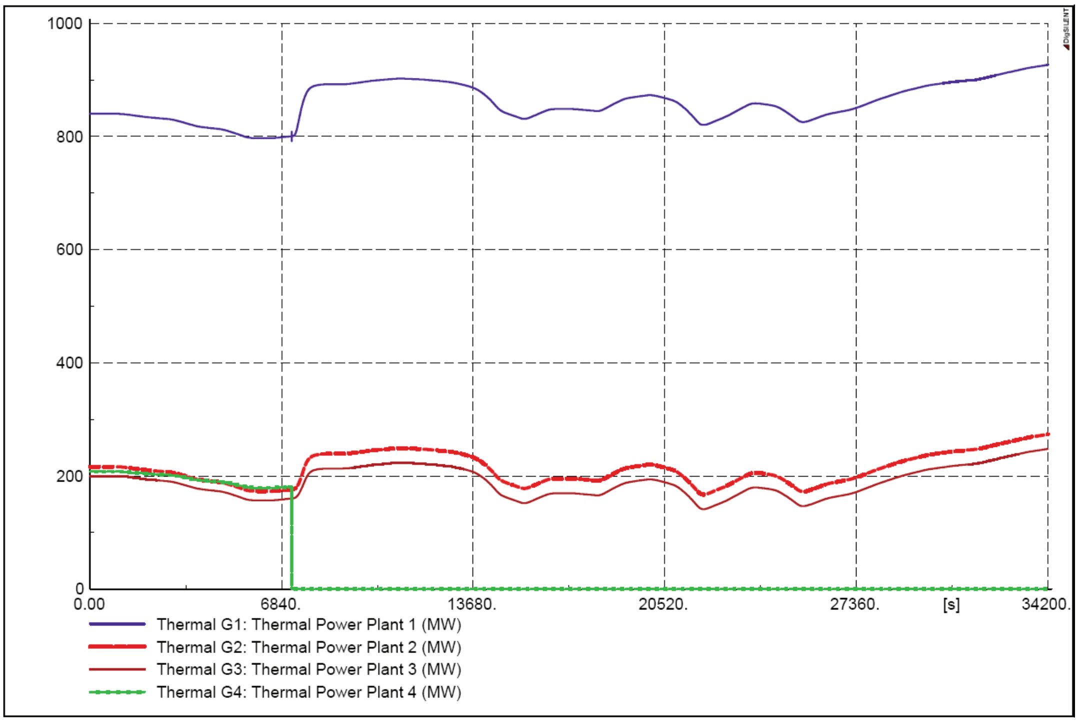


**Figure 7-29. Power productions from centralized power plants in case 4**

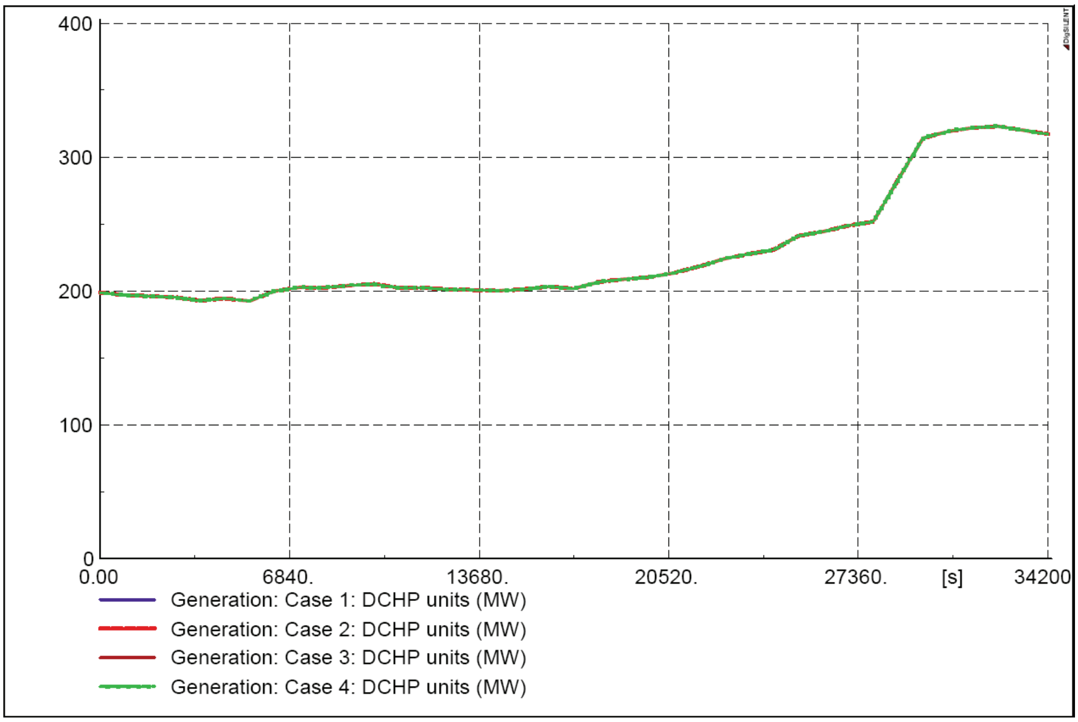


**Figure 7-30. Power generations from DCHP units**

# 7.5 Summary

In this chapter, an overview of dynamic sensitivity analysis is given. The dynamic sensitivity analysis of power generating units and power system operation are presented and discussed. The main part of this chapter is devoted to the evaluation of the simulation results of dynamic sensitivity analysis with regard to power balancing control. First, the simulation study of a centralized thermal power plant in the Danish power system is presented. Then, the dynamic sensitivity analyses of power system operations are carried out. Simulation studies with different share of centralized power plants and decentralized generating units are presented. Finally, N-1 analysis with regard to power balancing control in power system operations is given. In these power system dynamic simulations, the sensitivities of the outputs with respect to critical input parameters of ramp rate limiter, boiler time constant, and participation factors of AGC system, are indicated.

A simulation study of the centralized power plants is carried out. It can also be indicated that the unit response in long-term dynamic simulation is mainly determined by the ramp rate limiter component in the boiler turbine control model and also strongly influenced by the dynamic behaviour of the thermal boiler.

Simulation studies on the power system operations with different shares among the centralized thermal power plants show that the chosen *pf* value of the AGC system give a significant influence in the units' response. The deviations from planned power exchange with the UCTE system with different shares of the centralized power plants are presented. Simulation studies on power system operation with different share of decentralized power generating units show the capability of the secondary control of the DCHP units for improving the power balancing control. It can be seen that the DCHP units' capacity should be taken into account when planning the power balancing control. It can be expected that the power balancing control can be improved with the increasing of the DCHP generation capacities in the AGC system.

N-1 analysis is carried out to investigate the systems ability to withstand a loss of any single centralized thermal power plant, with regard to power balancing control. The deviations from planned power exchange with the UCTE system are brought back in the acceptable range of +/- 50 MW with in 500 sec. in all cases, due to the capability of the secondary control from the available generating units.

# Chapter 8
# System Analysis with Large Scale Wind Power Penetration

## 8.1 Introduction

In this chapter, an overview of the present status and the future status of the Danish power system with large scale wind power integration is presented. Power system simulation studies using the developed models and control strategies have be carried out in order to investigate the long-term system stability under the dynamic behaviour of the wind power sources. This chapter carries out a number of analyses with regard to the impacts of an increasing wind powers capacity in Denmark with the commissioning of the new offshore wind farms HRB and ROB and with a large scale wind power penetration which corresponds to 50% of Danish electricity consumption in 2025.

The main part of this chapter is devoted to the simulation studies of the Danish power system operations in long-term dynamic simulation with regard to power balancing control. First, simulation studies of the present status of wind power integration in Denmark are presented. A worst case scenario for the power system operation with HRA offshore wind farm and one also with commissioning of the HRB offshore wind farm are carried out. Then, simulation studies with an increased wind power capacity of 4.2 GW in Denmark are carried out, with a case scenario for normal operation and a worst case situation. Finally, a simulation study in the worst case situation with regulating power control, from the great belt link HVDC connection, is demonstrated.

The contribution of this chapter is the analysis of the Danish power system with large scale wind power penetration. Power system analyses using developed models of the Danish power system, power generating units, system interconnections, and the AGC system for long-term dynamic simulation are carried out. With the suitable control method, power deviation from planned power exchange at the Danish – German border should be kept in an acceptable limit.

# 8.2 Present status of wind power penetration

The present status of offshore wind power generations in Denmark, as illustrated in Figure 8-1, is presented in Table 8-1. The amount of wind energy in Denmark includes large offshore wind farms, an offshore wind farm HRA with 160 MW rated power in the western Denmark and an offshore wind farm ROA with 165.6 MW rated power in the eastern Denmark. The offshore wind power potential can be considered to be significant. More offshore wind farms will be installed in the future. The main increase in the wind power to be commissioned in the Denmark will come from the construction of new, large offshore wind farms. Commissioning of a new offshore wind farm HRB and a new offshore wind farm ROB has been announced by the Danish Energy Authority, with completion expected by the years 2009–2010 [8].

Commissioning of the offshore wind farm HRB with 215 MW rated power, in the same geographical area as the offshore wind farm HRA will increase the intensity of the wind power fluctuation and the deviation in the planned power exchange with the UCTE system. Large power deviation from planned power exchange can be expected. Therefore, the regulating power control and suitable control strategies are needed to prevent such a large power deviation in the future. With specified control methods, power deviation from planned power exchange with the UCTE system shall be kept in the acceptable limit of +/- 50 MW.


**Figure 8-1. Offshore wind farms in operation and in construction** [46]

TABLE 8-1
OFFSHORE WIND FARMS IN OPERATION AND IN CONSTRUCTION [46]

| No. | Wind Farms | Installed Capacities (MW) | No. | Wind Farms | Installed Capacities (MW) |
|---|---|---|---|---|---|
| **1** | **Vindeby** | 5 | **6** | **Rønland** | 17 |
| **2** | **Tunø Knob** | 5 | **7** | **Frederikshavn** | 8 |
| **3** | **Middelgrunden** | 40 | **8** | **Rødsand A** | 165 |
| **4** | **Horns Rev A** | 160 | **9** | **Horns Rev B (construction)** | 215 |
| **5** | **Samsø** | 23 | **10** | **Rødsand B (construction)** | 215 |

### 8.2.1 Simulation case scenario with HRA wind farm

Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generating units. These include the secondary control of the thermal power plants, as well as the fast secondary control from the DCHP units, to smooth out fluctuating power from wind turbines and increase the overall reliability of the power system.

In this study, the simulation study for a worst case scenario of the HRA wind farm is carried out. The main part of this section is devoted to the simulation studies of centralized power plants and DCHP units for long-term system stability. The parameters of the simulation study are provided as shown in Table 8-2. The simulation study to demonstrate what will happen if a large production from the HRA wind farm changes from maximum to zero at a certain load condition is of interest. Therefore, a worst case simulation study when a storm passed over the western Denmark is carried out.

Wind power productions from a wind farm HRA and wind speed passing over HRA wind farm are illustrated in Figure 8-2. The deviation from planned power exchange is illustrated as shown in Figure 8-3. Power generations from centralized thermal power plants and DCHP units are illustrated in Figure 8-4. Total wind power generations in the western Denmark are illustrated in Figure 8-5. Loads and power exchange with the Nordel system via HVDC connections is shown in Figure 8-6. Power productions generated from each centralized power plants are shown in Appendix C. Figure 8-7 shows the deviation from planned power exchange when the regulating power from the GBL is activated.

In Figure 8-2, the wind speed is seen to increase and reach the maximum speed of 25 m./sec. Therefore, the HRA wind farm is disconnected from the system at 27,900 sec. due to the high wind speed. Large deviation of 250 MW from planned power exchange with the UCTE system is caused by the disconnections of the large scale wind farm.

In this simulation study, only the centralized thermal power plants provide the secondary control, since the DCHP units are already operated at their maximum capacity due to the increased loads as shown in Figure 8-4. The power fluctuations from the aggregated wind power production on land can be much less intense than the offshore wind farms, due to the geographically distributed nature of wind production as shown in Figure 8-5.

TABLE 8-2
PARAMETERS IN POWER BALANCING CONTROL SYSTEM

| Power Plants | Active Power (MW) | pf |
|---|---|---|
| **Plant 1** | 1684 | 0.40 |
| **Plant 2** | 700 | 0.20 |
| **Plant 3** | 392 | 0.20 |
| **Plant 4** | 625 | 0.15 |
| **DCHP** | 400 | 0.05 |

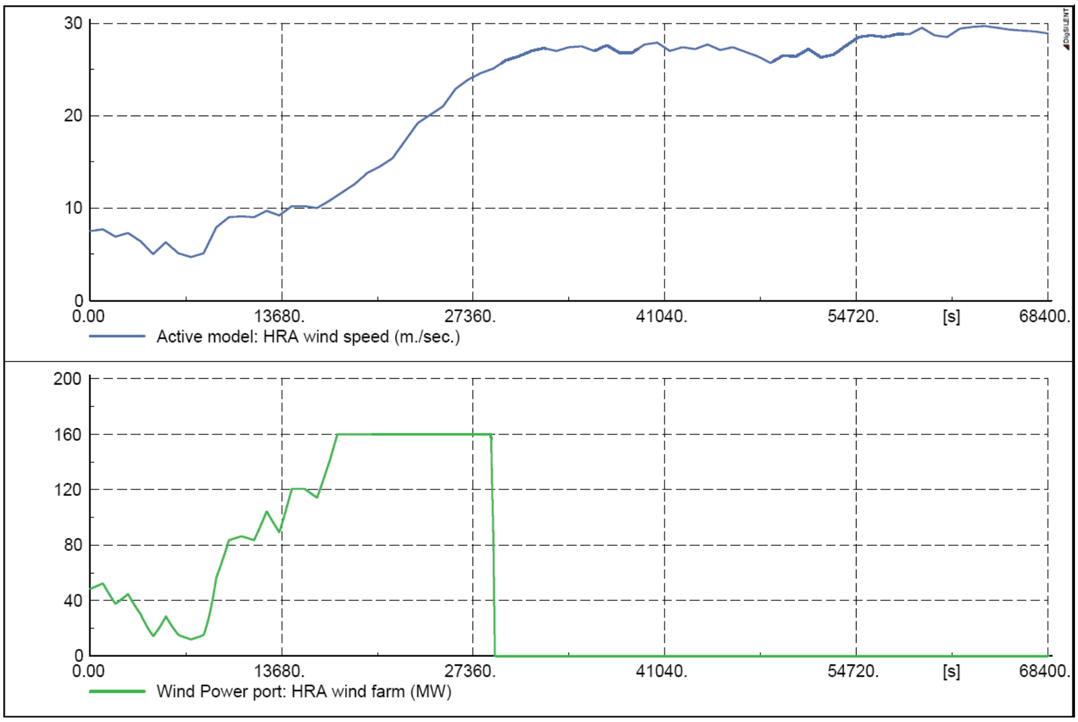


**Figure 8-2. Wind speed (above) and wind power generations from HRA wind farm (below)**

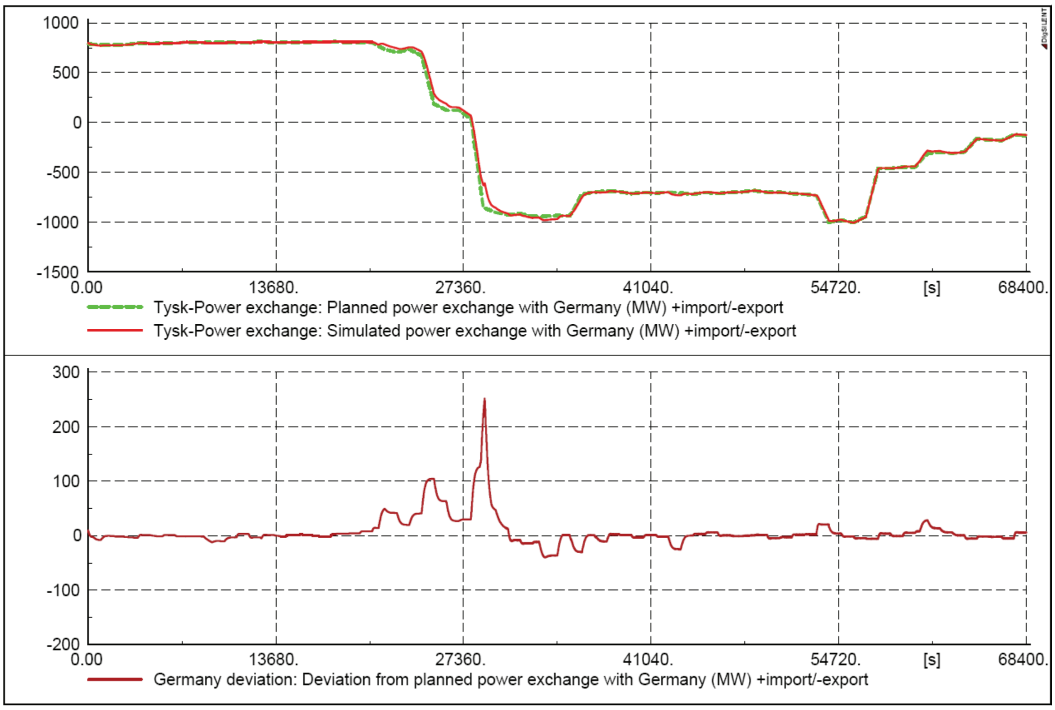


**Figure 8-3. Deviation from planned power exchange between ENDK-west and UCTE system**

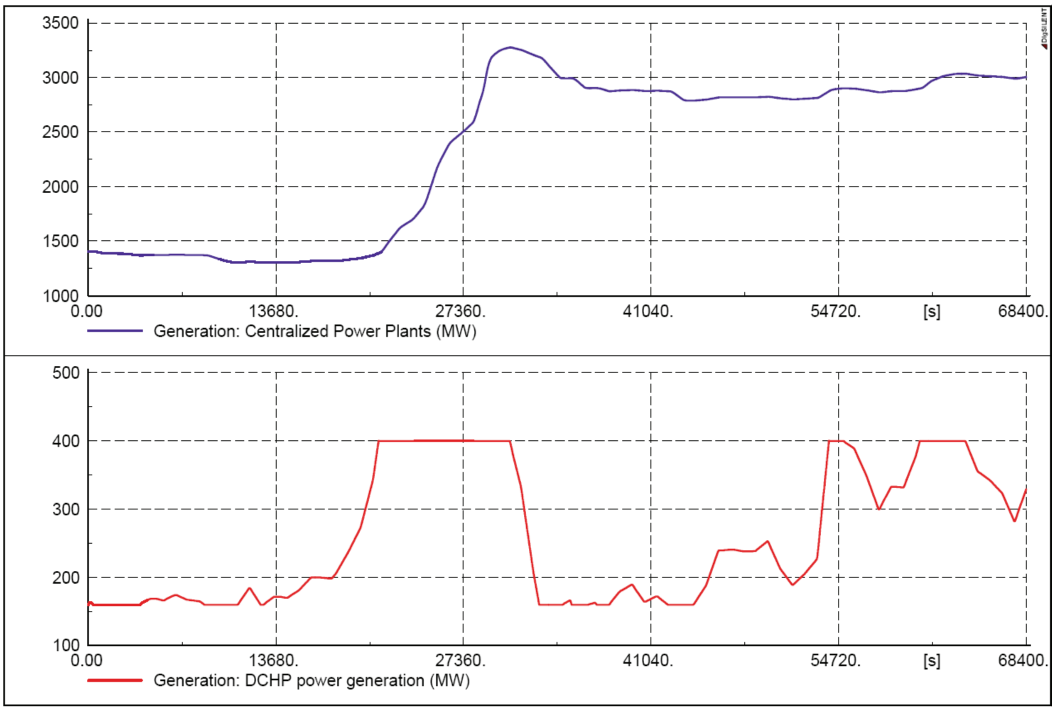


**Figure 8-4. Power generation from centralized power plants (above) and DCHP units (below) in ENDK-west area**

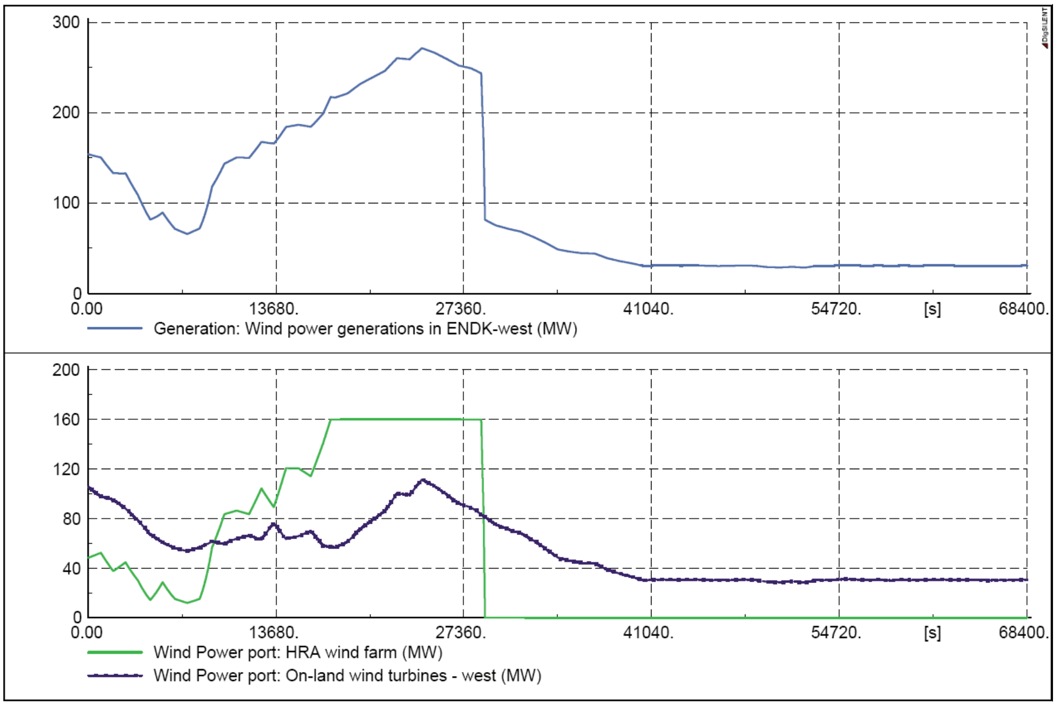


**Figure 8-5. Total wind power generations (above) and power generation from HRA wind farm and on-land wind turbines (below)**

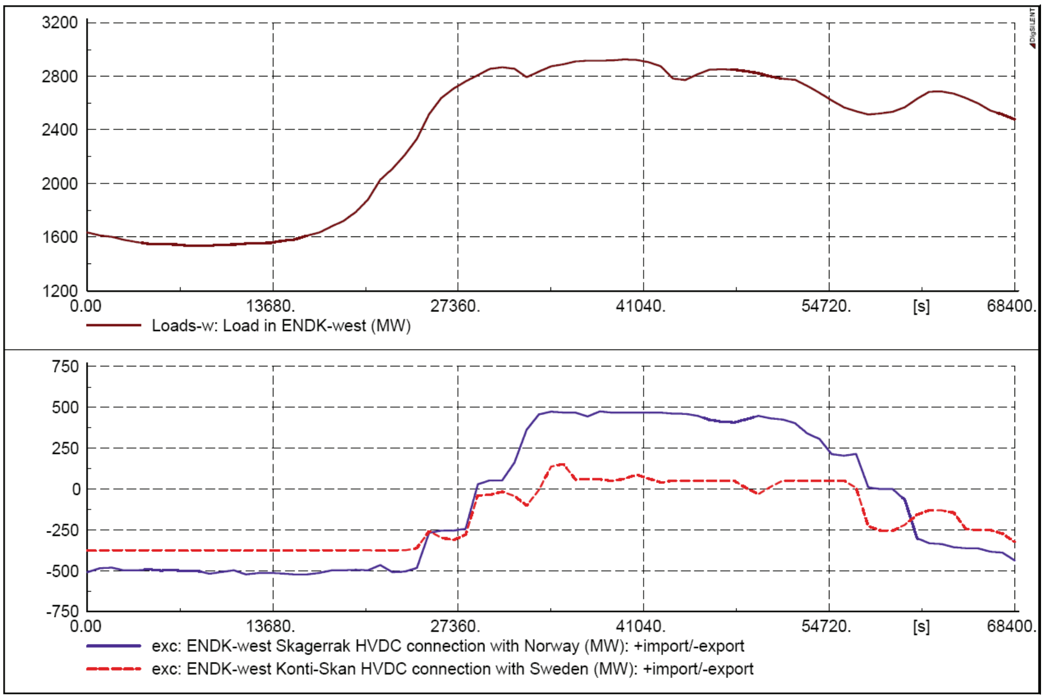


**Figure 8-6. Power exchange via the HVDC connections with Nordel system**

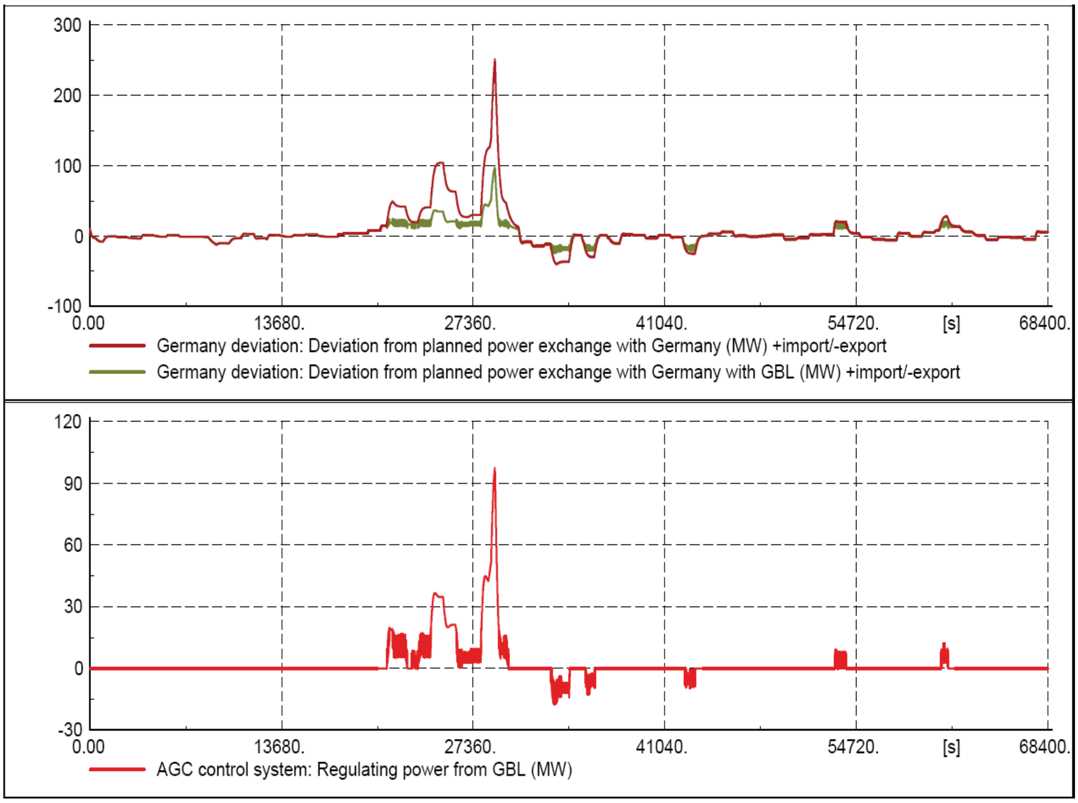


**Figure 8-7. Comparison between deviation without and with regulating power from GBL connection (above) and regulating power control provided from GBL (below)**

In this simulation study, the utilization of the regulating power control of the domestic power generating units is examined. It can be seen that the regulating power control from the centralized thermal power plants and from the GBL connection can reduce a large amount of power deviation. With the regulating power control from the HVDC connection with the Nordel system, the deviation is expected to be kept with in an acceptable limit.

### 8.2.2 Simulation case scenario with HRA and HRB wind farms

In this section, the simulation study for the commissioning of the new offshore wind farm HRB with 215 MW rated power is carried out. A simulation study to demonstrate what will happen if a large production from the HRA and HRB wind farms change from maximum to zero at a certain load condition is of interested. Therefore, a worst case simulation study when a storm passed over the western Denmark is carried out. The parameters of the simulation study are provided as shown in Table 8-3.

Wind power productions from HRA and HRB wind farms, and wind speed passing over HRA and HRB wind farms are illustrated in Figure 8-8. The deviation from planned power exchange is illustrated as shown in Figure 8-9. Power generations from centralized thermal power plants and DCHP units are shown in Figure 8-10. Loads and power exchange with the Nordel system via HVDC connections are the same as the ones shown in Figure 8-6. Total wind power generations in the western Denmark are illustrated in Figure 8-11. Figure 8-12 shows the deviation from planned power exchange when the regulating power control from the GBL is activated. Power productions generated from each centralized power plants are shown in Appendix C.

In this simulation study, wind speed increases and reaches the maximum speed of 25 m/sec. Therefore, HRA and HRB wind farms are disconnected from the system at 27,900 sec. and at 30,600 sec. respectively, due to the high wind speed as shown in Figure 8-8. The two wind speed data time series for HRA and HRB wind farms are developed based on the distance between the two wind farms, which is expected to be about 5 to 10 km. [42]. A large deviation of 250 MW from planned power exchange with the UCTE system is caused by the disconnections of the large scale wind farms. In this simulation study, only the centralized thermal power plants provided the secondary control, since the DCHP units are already operated at their maximum capacity due to the increased loads as shown in Figure 8-6. The power fluctuations from the aggregated wind power production on land can be much less intense than the offshore wind farms, due to the geographically distributed nature of wind production as shown in Figure 8-11.

TABLE 8-3
PARAMETERS IN POWER BALANCING CONTROL SYSTEM

| Power Plants | Active Power (MW) | pf |
|---|---|---|
| **Plant 1** | 1738 | 0.40 |
| **Plant 2** | 700 | 0.20 |
| **Plant 3** | 392 | 0.20 |
| **Plant 4** | 625 | 0.15 |
| **DCHP** | 400 | 0.05 |

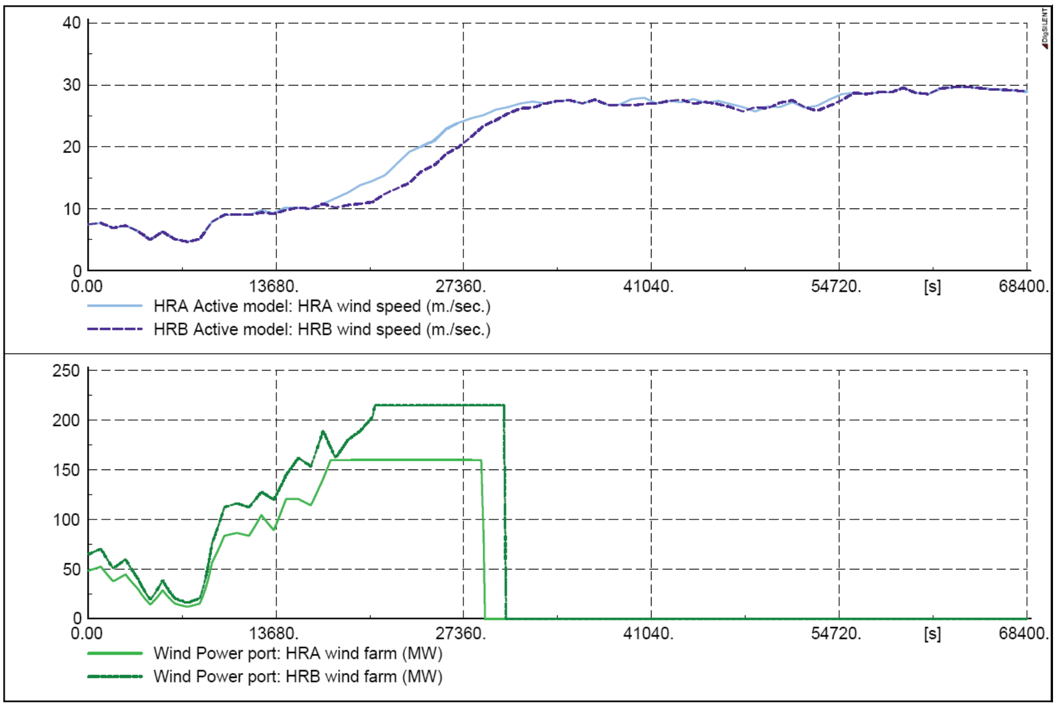


**Figure 8-8. Wind speed of HRA and HRB wind farms (above) and wind power generations from HRA wind farm and HRB wind farm (below)**

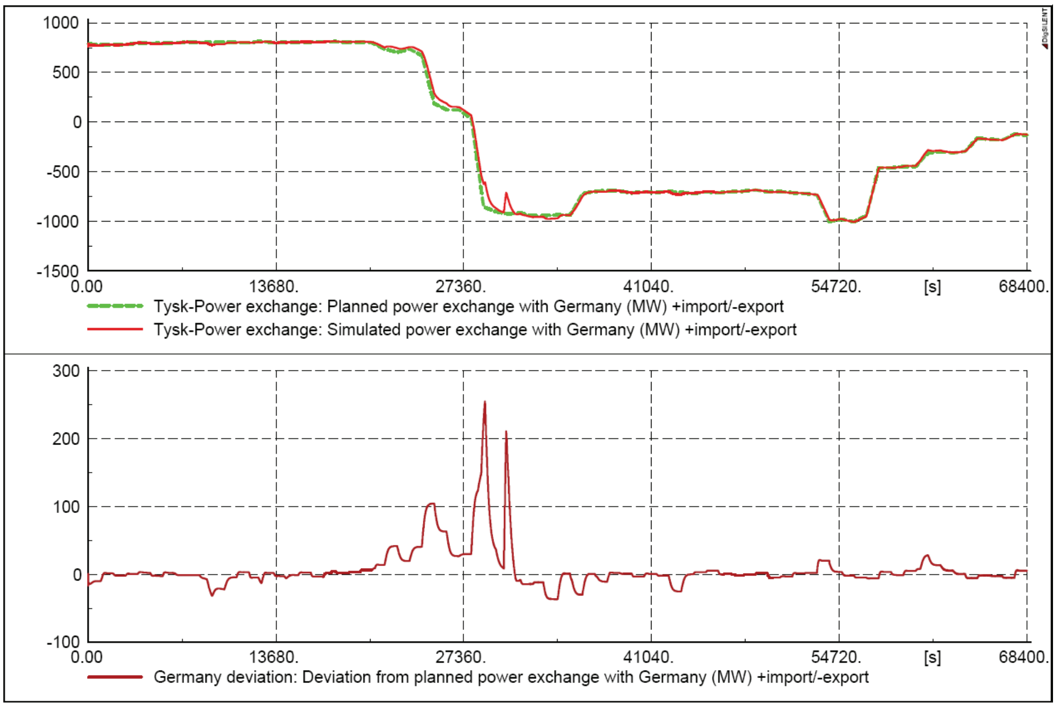


**Figure 8-9. Deviation from planned power exchange between ENDK-west - UCTE**

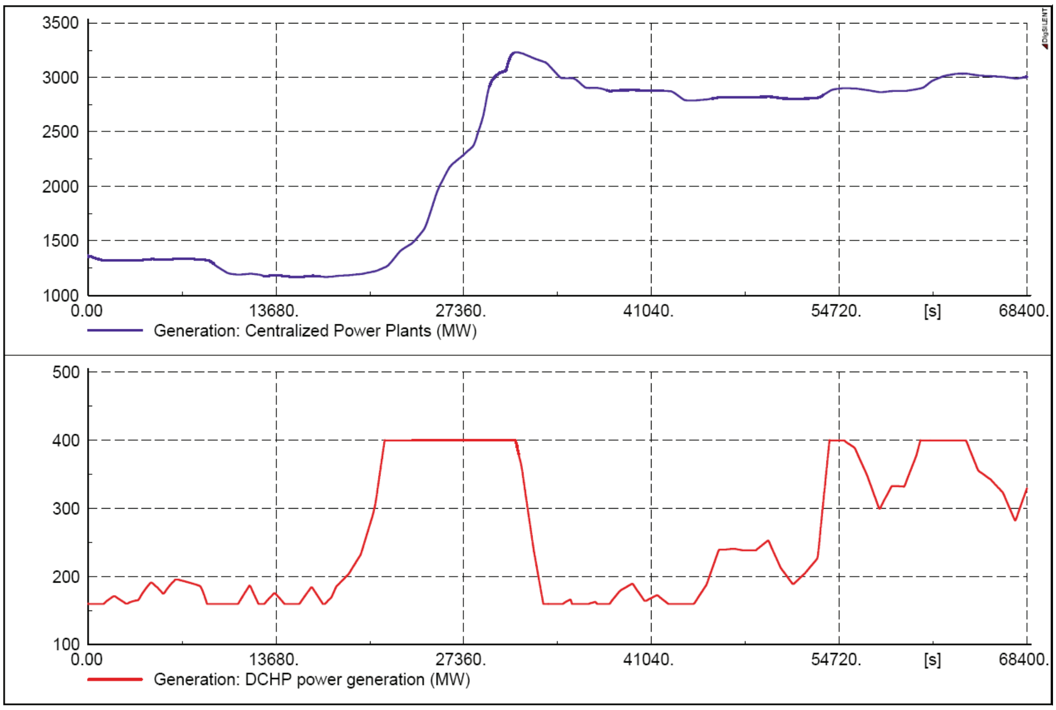


**Figure 8-10. Power generations from centralized power plants (above) and DCHP units (below)**

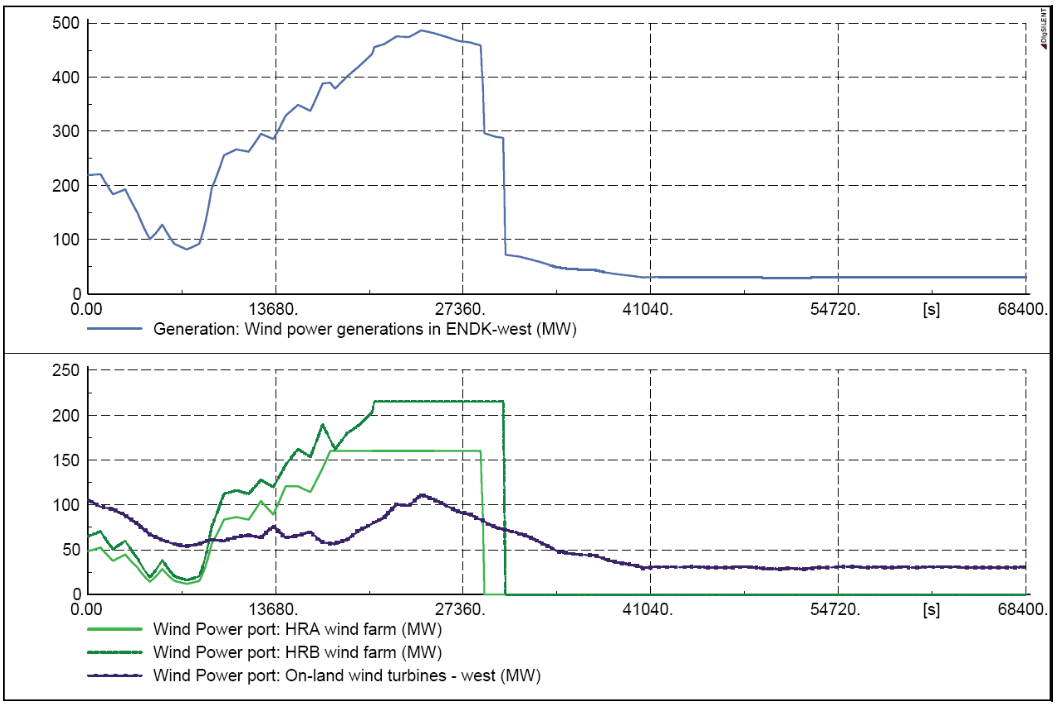


**Figure 8-11. Total wind power generation (above) and wind power generation from on-land wind turbines, HRA and HRB wind farms (below)**

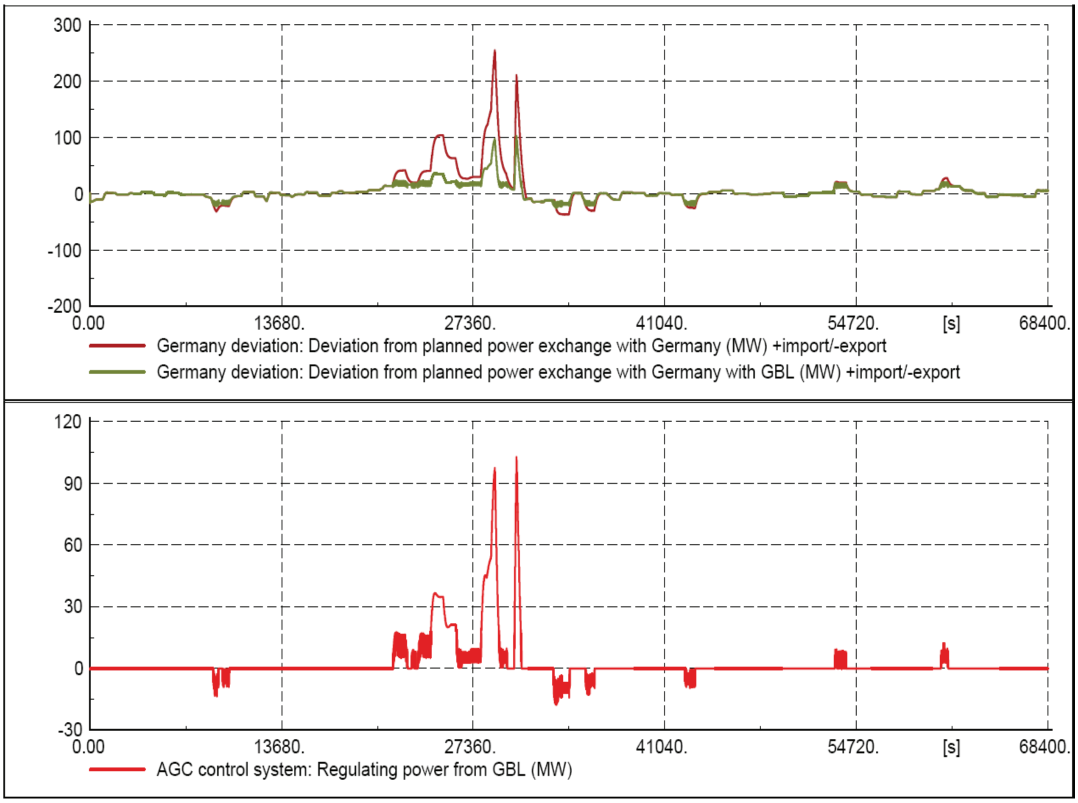


**Figure 8-12. Comparison of power deviations from the planned power exchange without- and with regulating power control from the GBL connection (above) and the regulating power provided from the GBL (below)**

In this simulation study, large power deviations due to the disconnection of 2 large offshore wind farms can be observed. This study is carried out based on the regulating control of the domestic power plants in a worst case scenario when the DCHP units are not available for the secondary control. It can be seen that the regulating power control from the GBL connection can reduce a large amount of power deviation. With the regulating power control from the HVDC connection with the Nordel system, the deviation is expected to be kept with in an acceptable limit.

# 8.3 Large scale wind power integration

A forecast made by the Elkraft system (Energinet.dk) shows that it is technically possible for Denmark to get 50% of its power from wind by 2025 [4]. Possibility to reach the limit of wind power installation as set by the Danish government in 2025, aims at installing 4 GW of offshore wind farms of which the largest part will be placed in the western area [46], [47]. With the increasing of large scale offshore wind farms, the power balancing control would be more challenging. Future status of wind power generations is shown in Figure 8-13 and in Table 8-4.

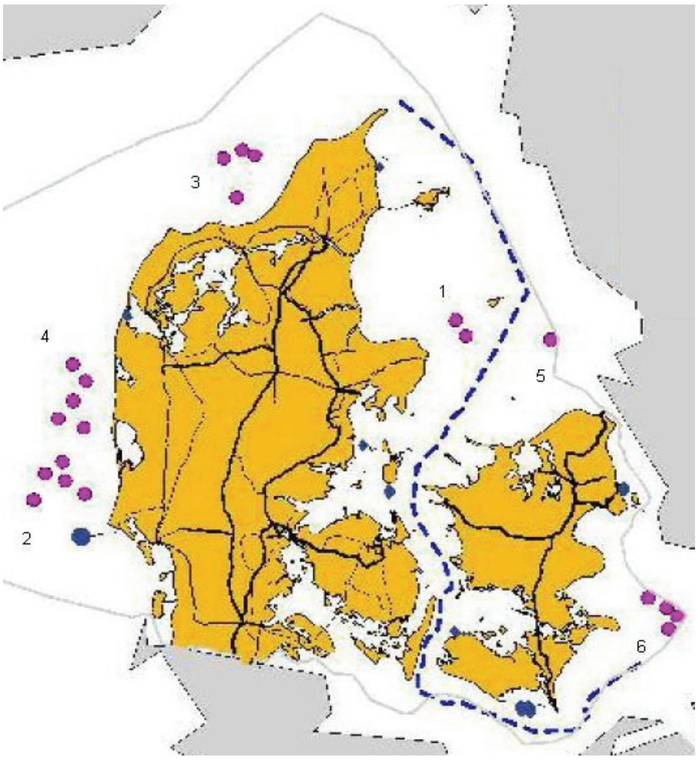


**Figure 8-13. New offshore wind farms in 2025 [46]**

TABLE 8-4
NEW OFFSHORE WIND FARMS IN 2025 **[46]**

| No. | Wind Farms | Installed Capacities (MW) | Total Capacities (MW) | Installed area |
|---|---|---|---|---|
| **1** | **Djursland** | 2*200 | 400 | ENDK-west |
| **2** | **Horns Rev** | 5*200 | 1000 | ENDK-west |
| **3** | **Jammebugt** | 4*200 | 800 | ENDK-west |
| **4** | **Ringkøbing** | 5*200 | 1000 | ENDK-west |
| **5** | **Store Meddelgrund** | 200 | 200 | ENDK-east |
| **6** | **Kriegers Flak** | 4*200 | 800 | ENDK-east |

### 8.3.1 Simulation study with 50% wind power penetration

The main part of this section is devoted to the simulation studies of power balancing control with large scale wind power penetration which corresponding to 50% of Danish electricity consumption. The control parameters of the simulation study are provided as shown in Table 8-5.

The simulation study to demonstrate what will happen if large offshore wind farms are installed in the Danish power system and operated at a certain load condition is carried out. In this study, 4.2 GW wind capacities are installed together with those present today (2007) in the Danish power system, this gives totally 6 GW [47] wind capacity. The additional 4.2 GW wind power are separately installed in ENDK-east with 1000 MW and ENDK-west with 3200 MW. The simulation study is carried out based on the current generation conditions (2007) in the Danish power system. Load condition is rescaled with 25% more of the time series data of one day in 2003.

Wind power productions from wind farms, and wind speed passing over wind farms are illustrated in Figure 8-14. The wind speed data time series for wind farms are roughly developed based on a wind speed time series of one day in 2003, and the distance between those wind farms, which shown in Figure 8-13. The deviations from planned power exchange are illustrated as shown in Figure 8-15. Power generations from centralized thermal power plants and DCHP units are shown in Figure 8-16. Load and power transaction with the Nordel system via HVDC connections is shown in Figure 8-17. Power productions generated from each centralized power plants are shown in Appendix C.

Large deviations up to 250 MW from planned power exchange with the UCTE system are caused by wind power fluctuation. In this simulation study, the secondary control for power balancing control is mainly provided by the centralized thermal power plants, since the DCHP units are already operated at their maximum capacity due to the increased loads as shown in Figure 8-16.

TABLE 8-5
PARAMETERS IN POWER BALANCING CONTROL SYSTEM

| Power Plants | Active Power (MW) | pf |
|---|---|---|
| **Plant 1** | 1738 | 0.40 |
| **Plant 2** | 700 | 0.20 |
| **Plant 3** | 392 | 0.20 |
| **Plant 4** | 625 | 0.15 |
| **DCHP** | 400 | 0.05 |

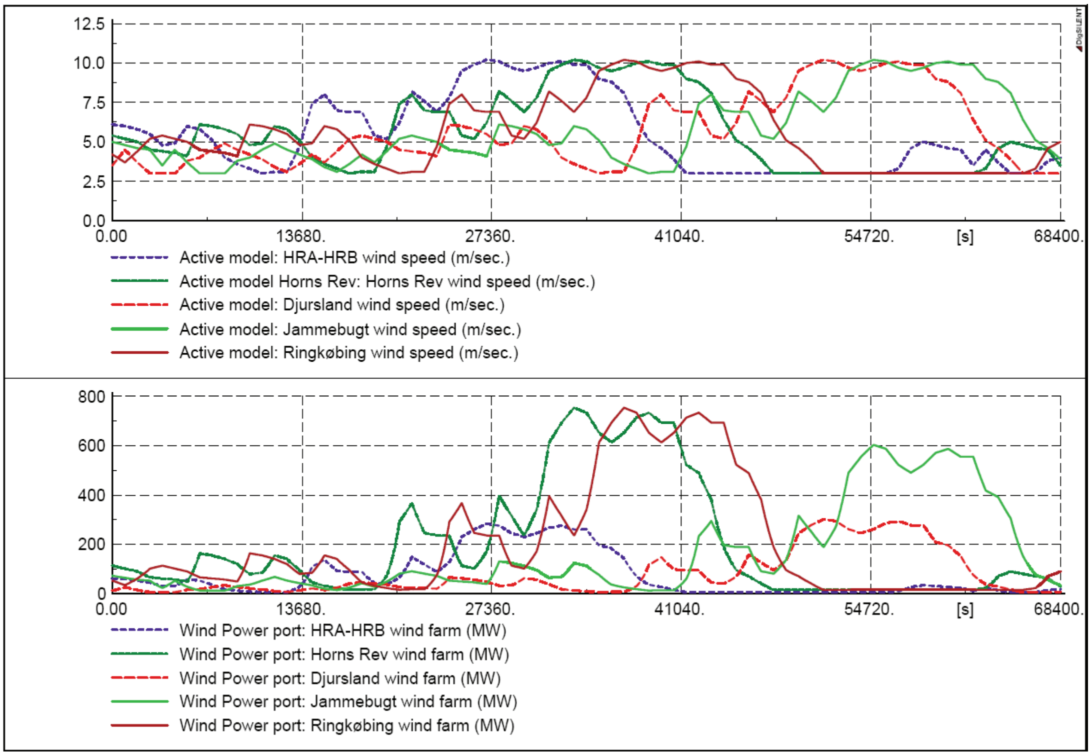


**Figure 8-14. Wind speed (above) and wind generations from wind farms (below)**

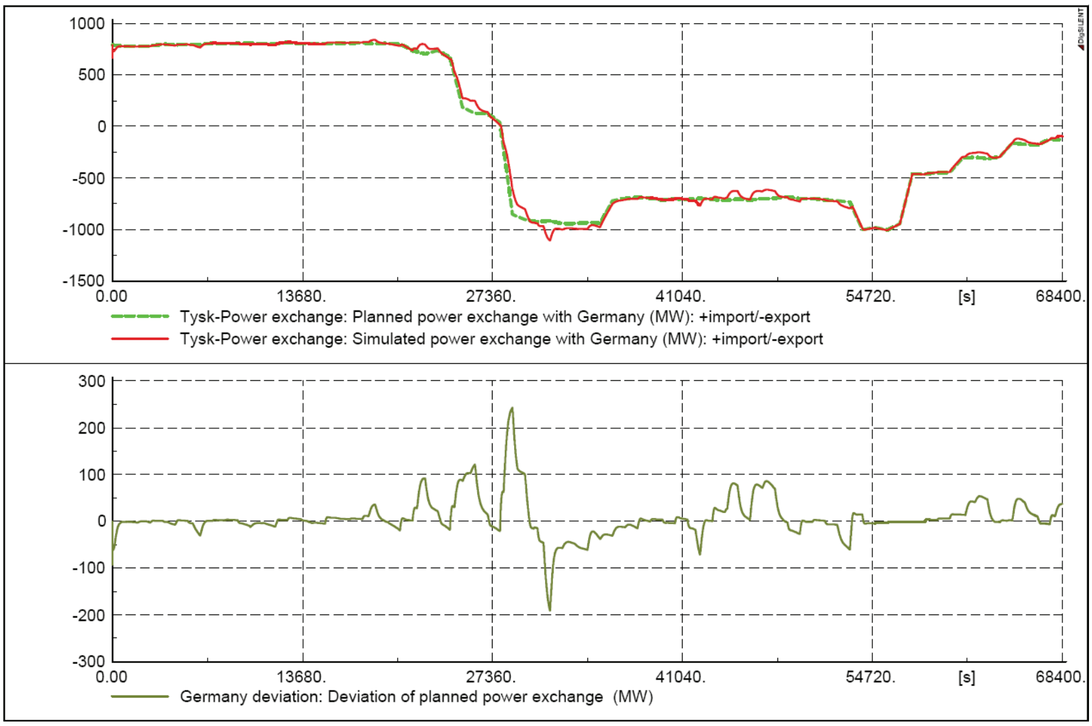


**Figure 8-15. Deviation from planned power exchange between ENDK-west - UCTE**

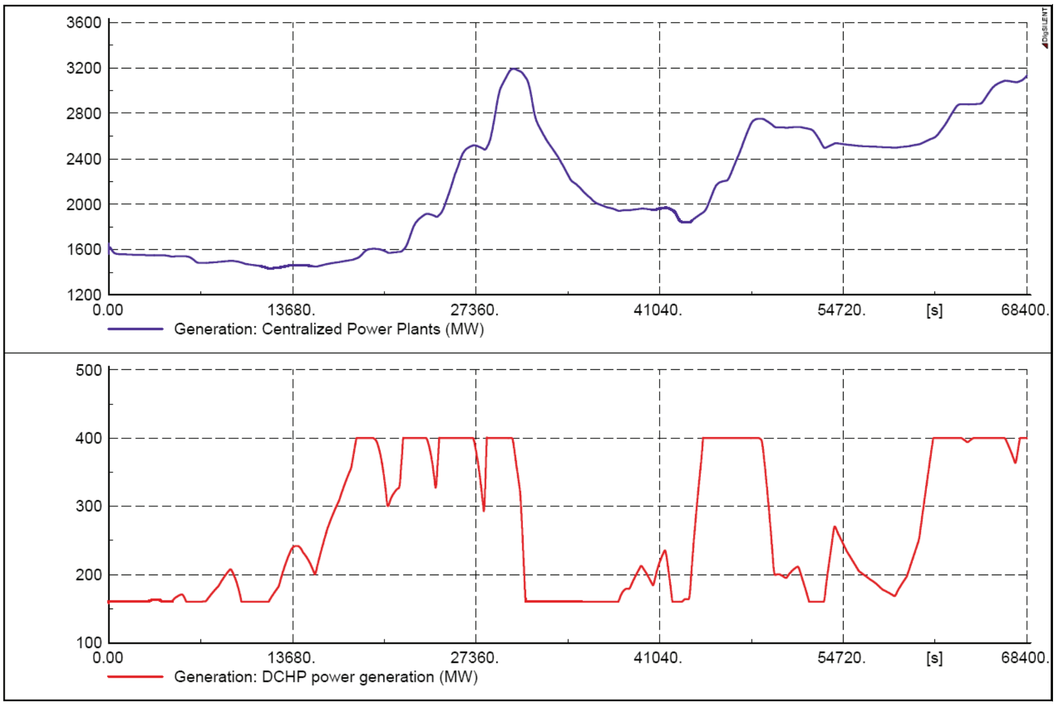


**Figure 8-16. Power generations from centralized power plants (above) and DCHP units (below) in ENDK-west area**

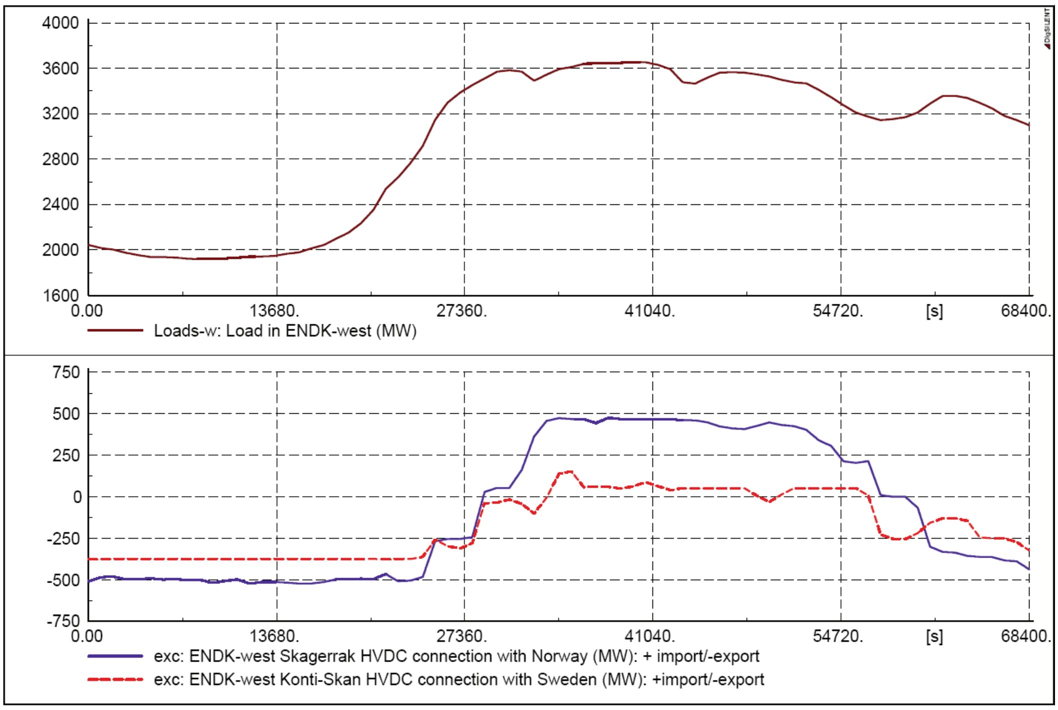


**Figure 8-17. Load (above) and power transaction via HVDC connections with the Nordel system (below)**

### 8.3.2 Worst case scenario with 50% wind power penetration

In this section, another simulation study for the integration of 6 GW wind power capacity is carried out. The main part of this section is devoted to the simulation studies of power balancing control in long-term dynamic simulation in worst case situation. This simulation study will demonstrate what will happen if a large production from the wind farms change from maximum to zero at a certain load condition.

The parameters of the simulation study are provided in Table 8-6. A simulation study for a worst case situation is when a storm passes over Denmark. The simulation study is carried out based on the current generation condition (2007) in the Danish power system. Load condition is again rescaled to 25% more from a time series data on one day in 2003. The power plant unit 4 is shutdown (for maintenance, etc.) in this study.

Wind speed passing over the wind farms and wind power productions from wind farms are illustrated in Figure 8-18 and Figure 8-19 respectively. The deviations from planned power exchange at the Danish – German border is illustrated as shown in Figure 8-20. Power generations from centralized thermal power plants and DCHP units are shown in Figure 8-21. Load and power exchange with the Nordel system via HVDC connections are the same as the ones shown in Figure 8-17. Power productions generated from each centralized power plants are shown in Appendix C.

Wind speed is increasing and reaches the maximum speed above 25 m/sec. Therefore, wind farms are disconnected from the system due to the high wind speed as shown in Table 8-7 and illustrated in Figure 8-19. Large deviation of 1,000 MW from planned power exchange with the UCTE system caused by the disconnections of large scale wind farms is introduced if the advantage of the GBL is not used. In this simulation study during t = 14,000 sec. to t = 17,400 sec., the centralized thermal power plants and the DCHP units are already operated at their minimum power production due to the increased wind power as shown in Figure 8-19. The power fluctuations from the aggregated wind power production on land can be much less intense than the offshore wind farms, due to the geographically distributed nature of wind generations.

TABLE 8-6
PARAMETERS IN POWER BALANCING CONTROL SYSTEM

| Power Plants | Active Power (MW) | pf |
|---|---|---|
| **Plant 1** | 1738 | 0.45 |
| **Plant 2** | 700 | 0.25 |
| **Plant 3** | 392 | 0.25 |
| **Plant 4** | 625 | - |
| **DCHP** | 400 | 0.05 |

Figure 8-22 show the deviation from planned power exchange when the regulating power control from the GBL is activated. The comparison between the deviations from planned power exchange without and with the regulating power control from GBL is shown in Figure 8-23. Regulating power control from the GBL is shown in Figure 8-24.

TABLE 8-7
DISCONNECTION TIME OF OFFSHORE WIND FARMS

| No. | Wind Farms | Capacities (MW) | Disconnection time (sec.) |
|---|---|---|---|
| **1** | **Djursland** | 400 | 36,000 |
| **2** | **Horns Rev** | 1000 | 29,700 |
| **3** | **Jammebugt** | 800 | 36,900 |
| **4** | **Ringkøbing** | 1000 | 31,500 |
| **5** | **Store Meddelgrund** | 200 | 36,900 |
| **6** | **Kriegers Flak** | 800 | 32,400 |
| **7** | **HRA and HRB** | 375 | 27,900 |
| **8** | **ROA and ROB** | 380 | 31,500 |

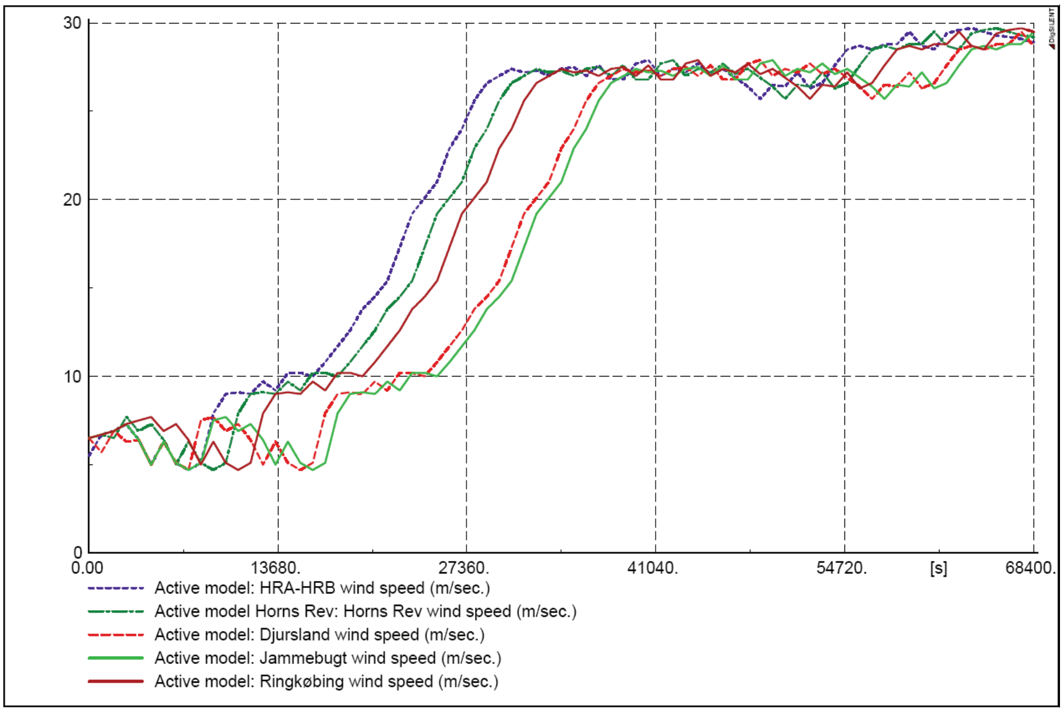


**Figure 8-18. Wind speed of wind farms**

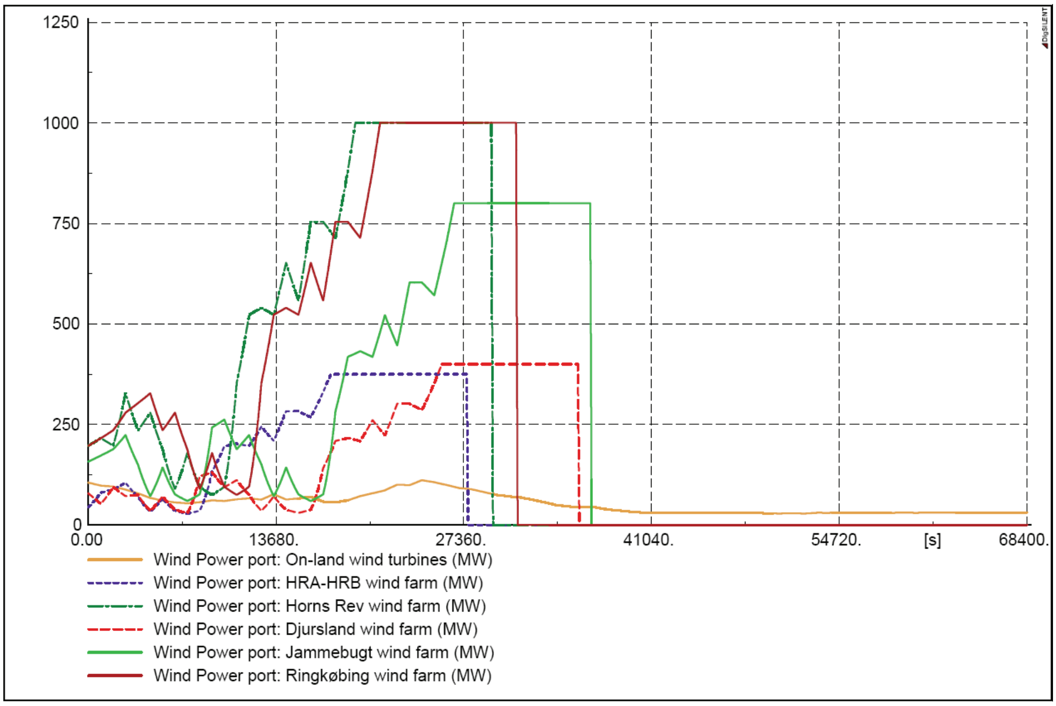


**Figure 8-19. Wind power generations from wind farms and on-land wind turbines**

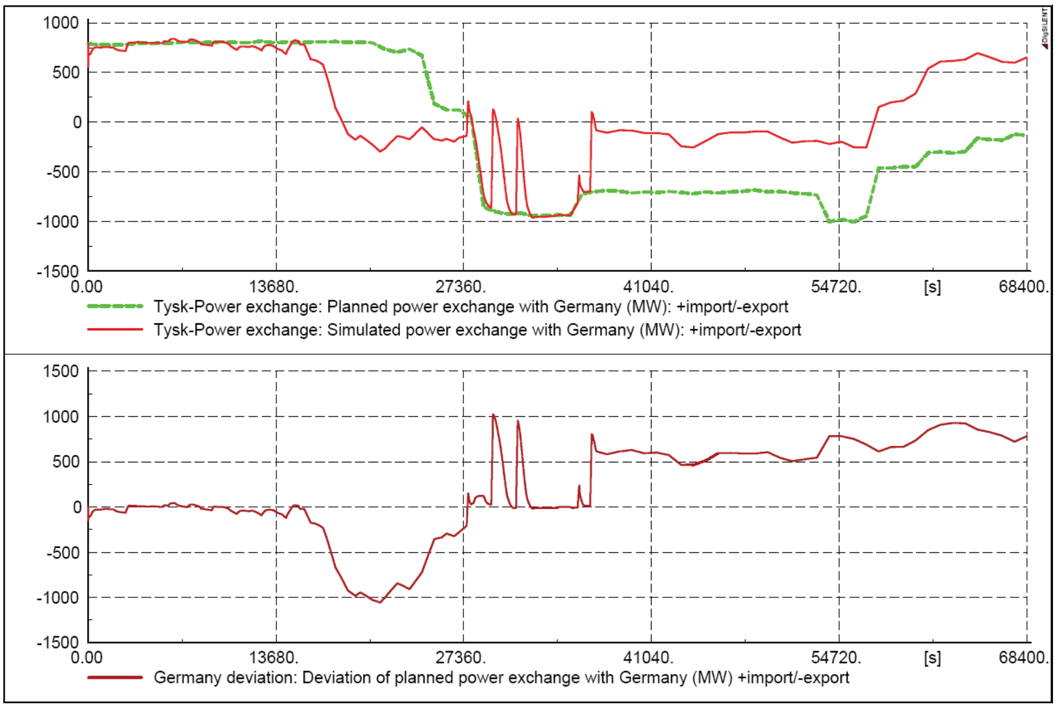


**Figure 8-20. Deviation from planned power exchange between ENDK-west and UCTE system**

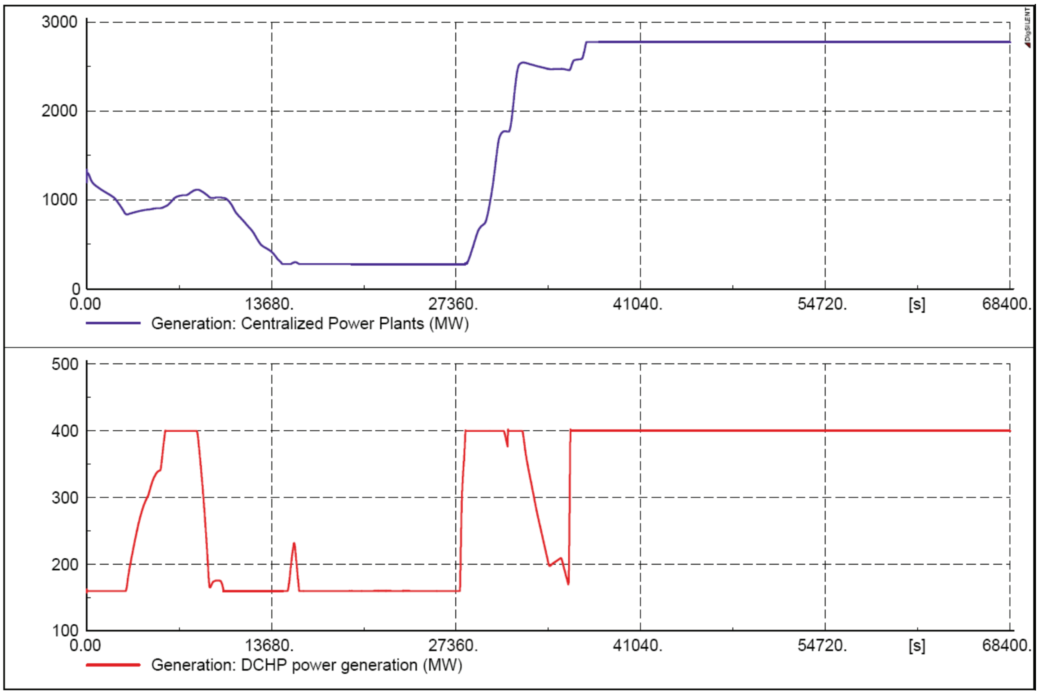


**Figure 8-21. Power generations from centralized power plants (above) and DCHP units (below) in ENDK-west area**

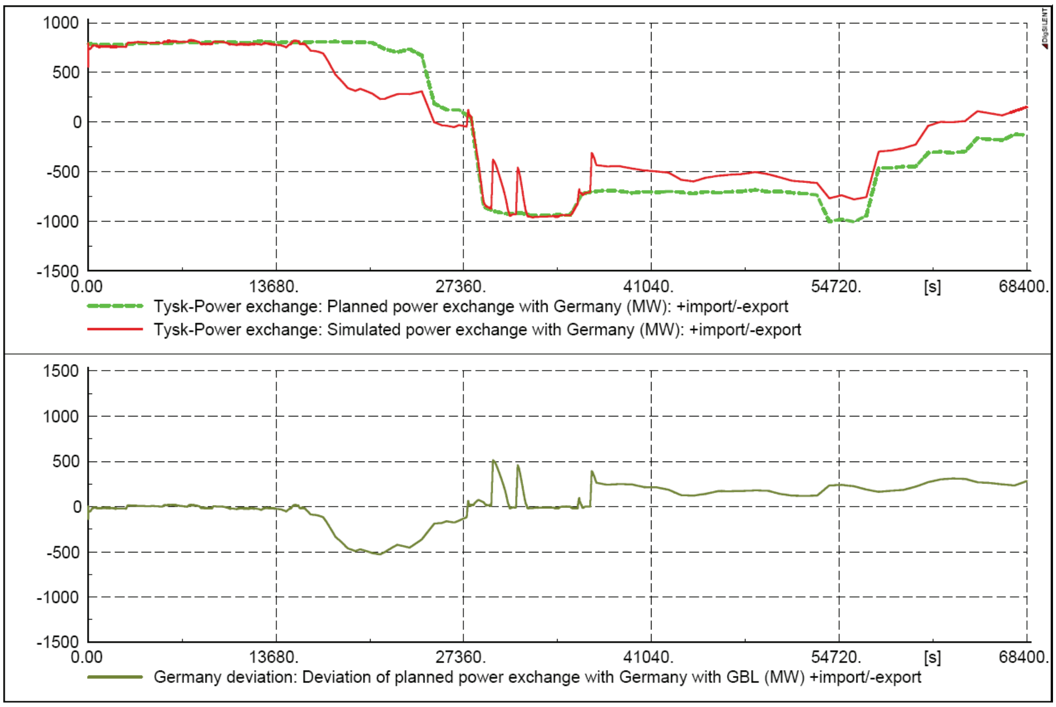


**Figure 8-22. Deviation from planned power exchange between ENDK-west and UCTE system with the GBL connection**

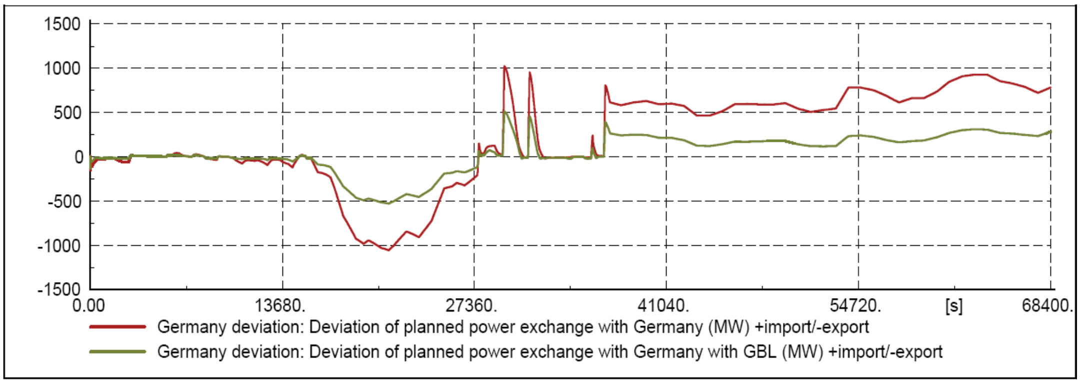


**Figure 8-23. Comparison between the deviation from planned power exchange between ENDK-west and UCTE system with and without the GBL connection**

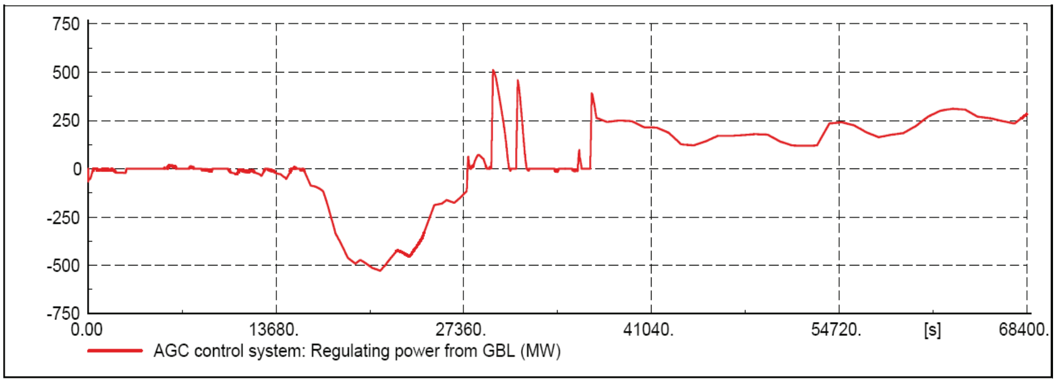


**Figure 8-24. Regulating power provided from the GBL connection**

In this section, a simulation study on the power system operation with large scale wind power integration with a worst case scenario has been carried out. The simulation result from the worst case scenario show the deviation from planned power exchange with the UCTE system. A simulation study on the power system operation with a large new wind power installation of 4.2 GW in Denmark shows the capability of the secondary control of the domestic power generating units for improving the power balancing control. The deviation from planned power exchange with the UCTE system caused by the disconnections of offshore wind farms due to the very high wind speed can be expected. Therefore, the better and more intense use of regulating power for power balancing control is required.

Detailed simulation results before and after the utilization of the GBL connection of power generations from each thermal power plant, power transaction between the eastern Denmark and Sweden are shown in Appendix C.

## 8.4 Summary

This chapter carried out a number of analyses with regard to impacts of increasing wind powers capacity in Denmark. Power system simulation studies using the developed models and control strategies are carried out in order to investigate the long-term system stability under the dynamic behaviour of the wind power sources. The developed model is used for the calculation of the exchanged power with the interconnected UCTE system. This model can also be used to investigate the system adequacy with regard to the exchanged power deviation with the interconnected systems at different loads and generations.

The main part of this chapter is devoted to simulation studies of the Danish power system operation in long term dynamic simulation with regard to power balancing control. First, simulation studies of the present status of wind power integration in Denmark are presented. A worst case scenario in power system operation with HRA wind farm and a worst case scenario with the commissioning of the new HRB wind farms are carried out. Then, simulation studies with increasing wind power capacity in Denmark to a productive volume corresponding to 50% of Danish electricity consumption in 2025 are presented. The case scenarios of normal operation and worst case operation are carried out. Finally, the regulating power control from the great belt link HVDC connection in the worst case scenario is demonstrated.

From the simulation studies, it can be concluded that the limit of wind power penetration can be analyzed with regard to the control strategies and the regulating power capability of generation units together with the reserve availability from the interconnected systems. Limit of wind power penetration in Denmark shall be specified with regard to the control methods. With the suitable control method, power deviation from planned power exchange at the Danish – German border shall be kept within an acceptable limit.

# Chapter 9

# Summary and Conclusion

## 9.1 Summary

### 9.1.1 Introduction of the project

Chapter 1 and Chapter 2 contain a general introduction of the thesis and of the Danish power system with large scale wind power penetration. An overview of the Danish power system is given. The general working principle of the system interconnections with the Nordel system and the UCTE synchronous area and technical specification of the great belt link HVDC connection between the eastern and the western Denmark are also presented. The challenge in Danish power system operation with regard to power balancing control issue is described. It is indicated that the Danish power system is characterised by a large degree of incorporation of dispersed generations such as DCHP units, on-land wind turbines and offshore wind farms. The main concepts of conventional thermal power plants and wind power generation in both on-land wind turbines and offshore wind farms, which depicts the dependence of the power generation on the wind speed, are described. Due to the difference between the conventional power plant technologies and wind power generations, the utilization of wind power affects a power system in several ways. It is expected that due to the large scale wind power penetration in Denmark, power fluctuation generated from wind turbines and wind farms may cause system impact on the Danish power system operation. This impact on the power balancing control can be observed at the Danish-German border.

Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generating units. These include the secondary control of the thermal power plants, as well as the secondary control provided from the DCHP units, to smooth out the fluctuating power from wind generators and increase the overall reliability of the power system. Further, the balance impacts differ for the various types of wind power generations, particularly for on-land wind turbines and offshore wind farms. The most interesting impact is the power fluctuations generated from large scale offshore wind farms which cause the imbalance at the Danish - German border. The power balancing control between the western Denmark and the UCTE system is indicated here as the focus of this thesis.

### 9.1.2 Development and implementation of models

Chapter 3, Chapter 4 and Chapter 5 contain procedures of implementation and development of models. The topic being interested in this research project is the impact of large scale wind power integration on power balancing control in the Danish power system. The shortest time constants in electrical power system are in millisecond, while the measurements of generations and loads used in the project are in time series of 30 seconds up to 15 minutes. In order to observe the phenomena of interest, a relative long-term simulation is necessary. Therefore, a simulation approach has been developed which is referred to as long-term power system dynamic simulation.

The use of aggregated models reduces the modelling effort and the amount of parameters. It also eliminates the necessity to specify unnecessary data for each generating units in the system. The aggregated models are particularly developed for using in long-term dynamic simulation and contain all subsystems and time constant that are of importance in these simulations. The developed Danish power system model is intended to use for the calculation of the imbalance with the interconnected UCTE system. This model can also be used to investigate the system reliability and system adequacy with regard to the deviation from planned power exchange with the interconnected systems at different load and generation conditions.

A model of an AGC system with wind power integration for dynamic power system simulation in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources is developed. The Generation Control Error (GCE) in the AGC presented the deviation of wind power generation and the deviation from planned power exchange with the UCTE system. The selection of the unit set-point is based on the generating units' ramping capability and the regulating electricity market conditions determined by the participation factors. However, the regulating electricity market condition and the unit commitment are not concerned in this project. From the simulation study, it can be seen that the degree of units' responses are very dependent on the participation factor used together with the AGC system.

An aggregated model of the centralized thermal power plants for AGC purpose is implemented. The regulating power control of a thermal power plant with ramp rates capabilities and unit time response is presented. It has been found that the unit response for long-term dynamic simulation is mainly determined by the ramp rate limiter in the boiler turbine control model together with the dynamic behaviour of the thermal boiler model, while other components, such as a speed governor model and a steam turbine model in the thermal power plant are used for improving the real response and maintaining the physical structure of the thermal power plant model. An aggregated model of the DCHP unit for AGC purpose is developed and integrated within the AGC system. A fast secondary control can be provided from the DCHP units. It can be observed that the fast unit response is mainly determined by the ramp rate in the power limitation block of the gas turbine dynamic model.

A simplified model of on-land wind turbines and an aggregated wind farm model with wind farm power control system are implemented. The simplified model of on-land wind turbines is modelled as a negative load with time series data from the measurements. In an aggregated wind farm model, it has been found that the model structures apply to the equivalent transfer function and several power control modes is suitable for long-term dynamic simulation. It can be observed that the most relevant dynamic of the units' response is due to the power gradient control and the time constant in active power control block. The model is suited to simulate the impact of wind speed fluctuations on the power system, and the grid support capabilities of a wind farm in normal operation and during grid disturbances.

The control topology of the system interconnections with the UCTE area and the Nordel system are presented. An overview structure and technical requirement of the Great Belt Link HVDC connection is described. The system interconnections between the Danish system and the UCTE area and the system interconnections with the Nordel system are included in the Danish power system model. The new settlement model introduces restriction on the use of the fast power control of the HVDC connections with the Nordel system.

However, this project focus is on the regulating power control within the Danish power system operation for the power balancing control at the Danish – German border. Therefore, the power transaction between the Danish power system and the Nordel system is included in the Danish power system model as a time series data of planned power exchange. It is in this way assumed that the HVDC connections with the Nordel system are operated according to their planned power exchange. The system interconnection between the western Danish power system and the UCTE synchronous area is modelled as a slack-bus with the measurement of planned power exchange with the UCTE system. The power deviation from planned power exchange can be observed on this slack-bus.

A model of the great belt link HVDC connection for long-term dynamic simulation considering the regulating power control capability is implemented. The utilization of the regulating power control incorporated in the eastern Denmark is expected to work together with that established in the western Denmark. The limit of regulating power control from the eastern Denmark via the GBL is restricted with the deviation of planned power exchange between the eastern Denmark and the Nordel system via the AC cables.

The developed AGC system model has been successfully validated against the measurement. This gives confidence in the developed AGC model and shows that the result of the applied simulation is acceptable. The aggregated models of centralized power plants and DCHP units are validated in dynamic simulation in order to compare simulation results with measurements and to investigate the influence of the participation factors of the AGC system. It can be observed that the model is reasonably accurate and can be used in long-term power system dynamic simulation.

The wind turbine level in an aggregated wind farm model is validated by comparing the simulation results with that of a detailed wind turbine model. The comparison is based on the active power generation as function of the variation of wind speed. The agreement between the responses of the aggregated and detailed models of power generating units is rather close. It can be concluded that the aggregated model can be used to represent wind farms in long-term dynamic simulations.

For long-term dynamic simulation, the accuracy achieved from all aggregated models, developed in this project, is sufficient. The level of correspondence between simulations with the developed models and measurements proved to be satisfactory. It was therefore decided to use the models for this project.

### 9.1.3 Control strategies

Chapter 6 contains a general introduction of the system control strategies for power balancing control. On large interconnected systems, power balancing problem is one of the main challenges. The major issue in this research project is to comply with the fluctuating nature of wind power production. The impacts of power fluctuations from large scale wind farms on the power system with regard to the power balance control have been presented and discussed with different control strategies. The utilization of the domestic regulating power resources is among the vital arrangements for better power balancing. This includes utilization of the fast secondary control from the DCHP units and activation of the power control of the offshore wind farms which includes the power gradient limit and the delta production control.

The utilization of the centralized thermal power plants with the secondary control of the available thermal power plants is carried out. This analysis has shown the capability of the available thermal power plants which nearly eliminate the power deviations with the UCTE system. Then, the utilization of the secondary control of the available thermal power plants and the utilization of the secondary control from DCHP units are also carried out. This analysis has shown even better capability of the available regulating power which decreases the power deviations with the UCTE system even more. The utilization of wind power control with the use of the power gradient limit together with the Delta control on HRA wind farm is presented. This analysis has shown the slightly better capability of the power balance control which decreases the power deviations with the UCTE system.

A simulation study with the commissioning of the new offshore wind farm HRB, in the same geographical area with the HRA wind farm is carried out. The establishment of the GBL will make it possible to utilize the regulating power control incorporated in the eastern Danish system to work together with that established in the western Danish system. The utilization of the AGC system accessing the secondary control of the thermal power plants, the secondary control of the DCHP units and the GBL HVDC connection is demonstrated. This analysis has shown the better capability of the available regulating power which decreases the power deviations with the UCTE system.

The limit of wind power penetration can also be analyzed with regard to the specified control strategies and the regulating power capability of generating units together with the reserve availability from the interconnected systems. It can be concluded that the control strategies, which allows for active power balance might set up a limit for the wind power penetration.

### 9.1.4 System analysis

Chapter 7 and Chapter 8 are devoted to simulation studies with regard to the impacts of wind power on power balancing control. The model developed in chapter 3, chapter 4 and chapter 5 are used in the simulation studies and system analysis. The main part of chapter 7 is devoted to the evaluation of the simulation results by dynamic sensitivity analysis. First, a simulation study of the conventional thermal power plants, based on different characteristics in ramp rate and boiler time constant, is presented. Then, a dynamic sensitivity analyses on power system operations are carried out. Simulation studies with generation dispatch of centralized power plants and decentralized combined heat and power units, including different share of centralized power plants and different share of decentralized CHP units, are presented. Finally, an N-1 analysis with regard to power balancing control issue is carried out.

In these simulation studies in power system dynamics, the sensitivities of the outputs with respect to critical input parameters of ramp rate limiter, boiler time constant, and participation factors (*pf*) of the AGC system, are indicated. It can also be indicated that the response of a centralized power plant unit in the dynamic simulation is mainly determined by the ramp rate limiter component in the boiler turbine control model but also strongly influenced by the dynamic behaviour of the thermal boiler. The results from this simulation study also show the characteristic of centralized power plants in the western Danish power system. Simulation studies on power system operations with different share of centralized thermal power plants show that the chosen *pf* values of the AGC system give a significant influence in a unit's response.

The deviations from planned power exchange with the UCTE system with different share of the centralized power plants are presented. Simulation studies on power system operation with different share of decentralized power generating units show the capability of the secondary control of the DCHP units for improving the imbalance. It can be seen that the DCHP units' capacity should be taken into account when planning the power balancing control. It can also be expected that the power balancing control will be improved with the increase of DCHP generation capacities in the AGC system. An N-1 analysis is carried out to investigate the system ability to withstand a loss of any single centralized thermal power plant, with regard to power balancing control. The deviations from planned power exchange with the UCTE system are brought back in the acceptable range of +/- 50 MW with in 500 sec. in all cases with regard to ramp rates and time constants of generating units. This simulation study also shows the capabilities of the generating units to maintain the power balance control when such situations happen.

The main part of chapter 8 is devoted to a long-term dynamic simulation of the Danish power system operated with large scale wind power penetration. The power system analyses by using the developed models of the Danish power system, the power generating units, the system interconnections, and the AGC system for long-term dynamic simulation are carried out. First, the simulation studies of the present status regarding wind power integration in Denmark are presented.

The worst case scenario in power system operation including the HRA offshore wind farm and the newly commissioned HRB offshore wind farm are carried out. This simulation study demonstrate what will happen if a large production from wind farms change from maximum to zero at a certain load condition. The capabilities of the secondary control and the regulating power control from different generating sources can be observed. Next, simulation studies with an increasing wind power capacity of 4.2 GW in Denmark, with a case scenario in normal operation and one in worst case situation, are carried out. Finally, a simulation study in a worst case situation, using the regulating power control from the great belt link HVDC connection, is demonstrated.

This analysis has shown the capability of the available regulating power which decreases the power deviations with the UCTE system. However, this simulation is carried out based on the AGC system, with power gradient control on wind farm. Planned wind power control, delta control and balance control on the wind farms are not taken into account in this simulation. Therefore, the wind power is generated from wind farms according to variable wind speed. This simulation study intends to show what will happen in a very worst case situation when the domestic power regulating control is used. It can be expected that the capability of power balancing control can be improved with the utilization of the regulating power control from the system interconnection with Nordel and the utilization of the planned power control in wind farm including balance control and delta control.

From the simulation studies, it can be concluded that the limit of wind power penetration can also be analyzed with regard to the specified control strategies and the regulating power capability of generating units together with the reserve availability from the interconnected systems. Limit of wind power penetration in Denmark shall be specified with regard to the control methods.

## 9.2 Conclusion

This wind power integration project contains significant advances in the power balancing control analysis. In most large power systems, multiple individual balancing areas coordinate their activities to maintain reliability and conduct transactions of electric power. A balancing area consists of generating units, loads, and system interconnections to neighbouring areas. The balancing area assists the system interconnection with maintaining system frequency and balances generation and load. Power system simulation studies using the developed models and control strategies are carried out in order to investigate the long-term system stability under the dynamic behaviour of the wind power sources. The developed model is used for the calculation of the exchanged power with the interconnected UCTE system.

Dynamic simulation studies indicated that real time regulating power control can reduce power imbalance caused by wind power generation by providing access to additional resources for the balancing control of wind power generation. Long-term system stability is examined using stability simulations of major disturbances, such as a forced outage of a large generating unit. Comparisons of study cases with different degree of wind power penetration and different access to a large number of generating units with significant ramping capability on the system showed improved long-term stability when wind power plants are part of the generation of mix.

From simulation studies, it can be observed that the domestic regulating power control has a limit capability to maintain the deviation from planned power exchange between the western Denmark and Germany within an acceptable limit of +/- 50 MW. It can be seen that the regulating power control from the GBL connection can reduce a large amount of power deviation. However, the available regulating power from the GBL is depend on the planned power exchange of the GBL connection, and the planned power exchange between the energinet.dk-east with the Nordel system. With the regulating power control from the HVDC connection with the Nordel system, the deviation is expected to be kept with in an acceptable limit. It can also be concluded that the control strategy, which allows for active power balance might set up a limit for the wind power penetration in Denmark.

## 9.3 Future Work

**Model Development**

As indicated in chapter 3, the AGC system model is developed for power balancing control. This AGC model is designed based on regulating power control regarding power balancing control issue. The selection of the power generating units is based on the generating units' ramping capability and the regulating electricity market conditions determined by the *pf*. For the future work, developed models of the unit commitment and generation dispatch can be used together with the utilization of the AGC system for power balancing power control instead of using the participation factors. The economic issue of the regulating electricity market conditions and available power plants should be taken into account, and the suitable *pf* values can be automatically calculated from the AGC system.

As indicated in chapter 5, the new settlement model introduces restriction on the use of the fast power control of the HVDC connections with the Nordel system. In this project, the power transaction between the Danish power system and the Nordel system is included in the Danish power system model as a time series data of planned power exchange as this project focuses on the regulating power control within the Danish power system operation for the power balancing control at the Danish – German border. A regulating power control based on the new settlement model for the interconnections with the Nordel should be developed. The regulated electricity market and economic issue can be taken into account in the model development. The condition of regulating power control via this HVDC condition with regard to power generations in Norway and Sweden can also be considered.

The great belt link model developed in this project is designed for long-term dynamic simulation with regard to power balancing control in the western Danish power system. The new model should also be developed for the regulating power control for the need of the eastern Denmark. The prioritization in the power control for the GBL connection for the need of the western Denmark and for the need of the eastern Denmark can be developed. The cooperation of the regulating power control between the utilization of the great belt link HVDC connection and the utilization of the regulating control on the HVDC connection with the Nordel system should be developed.

As indicated in chapter 8, wind speed data for all of wind farm are developed based on the time series data of measurements of the wind power productions in HRA wind farm on one day in 2003 for the normal operation and are roughly prepared for the worst case scenario. More realistic wind speed information for each wind farm can be prepared for the dynamic simulation, as the offshore wind farms are installed in different locations, and then the more accurate simulation result can be expected.

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# Appendix

## A. Model structure in DIgSILENT PowerFactory

Model developments are carried out in power system program DIgSILENT Power Factory. This Appendix shows the Figures of the developed models in DIgSILENT Power Factory.

The Danish power system model as a two bus-bar model is shown in Figure A-1. The AGC systems of the eastern Danish power system (Energinet.dk-east) and of the western Danish power system (Energinet.dk-west) are illustrated in Figure A-2 and Figure A-3 respectively.

The model of the future Danish power system in 2025 is shown in Figure A-4. The AGC systems of the eastern Danish power system in 2025 and of the western Danish power system in 2025 are illustrated in Figure A-5 and Figure A-6 respectively. The Great Belt Link HVDC connection is shown in Figure A-7.

An aggregated model of centralized thermal power plant with steam turbine and its components are shown in Figure A-8 to Figure A-12. A simplified model of the reactive power control is shown in Figure A-13.

An aggregated model of a decentralized Combined Heat and Power (DCHP) unit and its components are shown in Figure A-14 to Figure A-18.

An aggregated model of a wind farm model and its components are shown in Figure A-19 to Figure A-24.

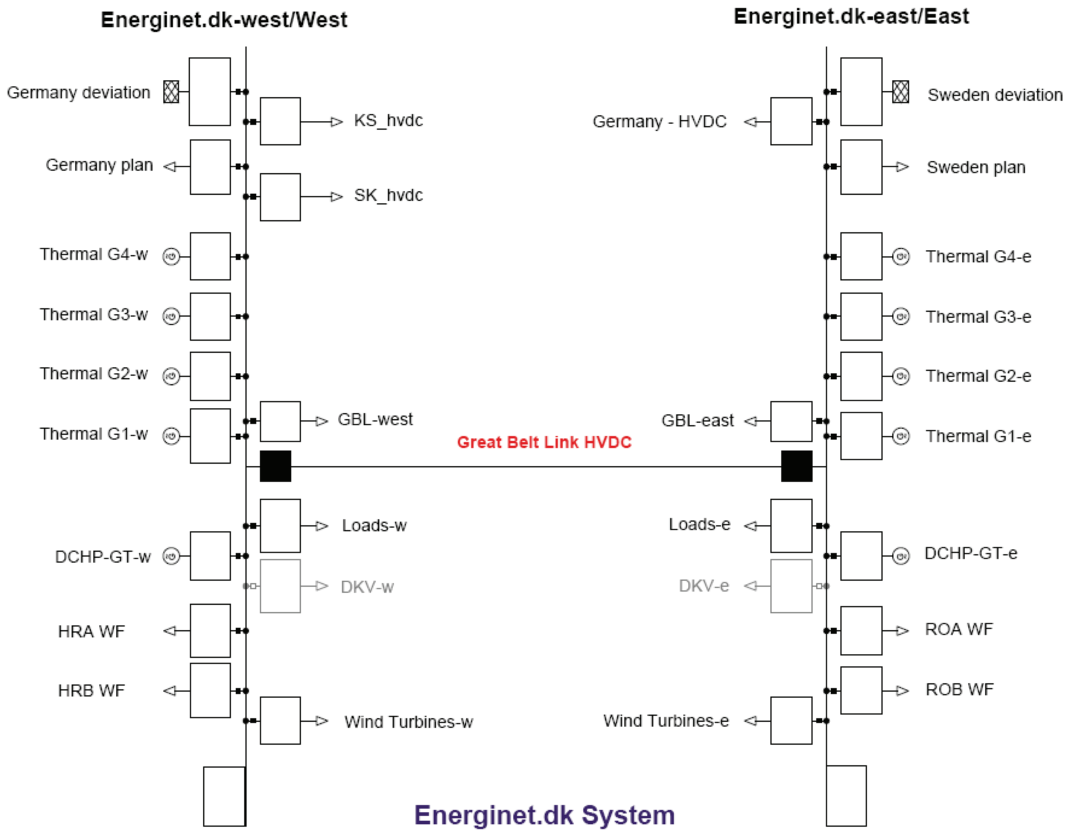


**Figure A-1. Energinet.dk – 2007**

The Danish power system model can be reduced to a two bus-bar model, with different power generating units, such as thermal power plants, DCHP units, on-land wind turbines, offshore wind farms, and loads.

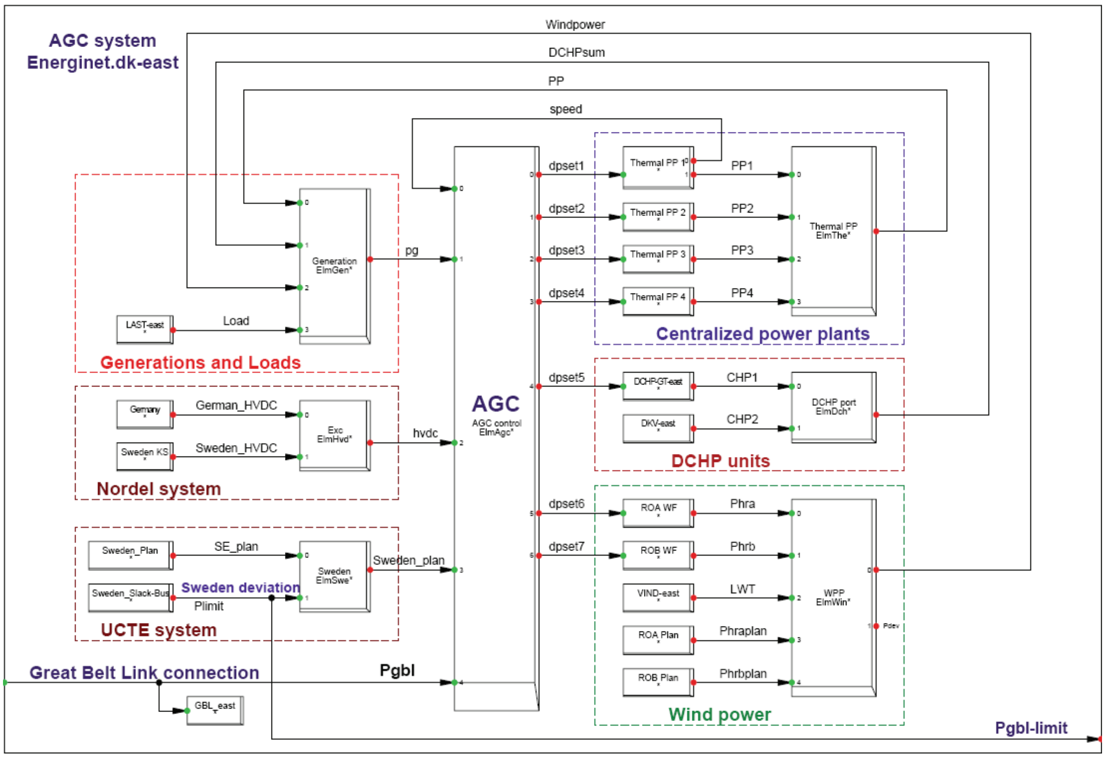


**Figure A-2. AGC system: Energinet.dk – east in 2007**

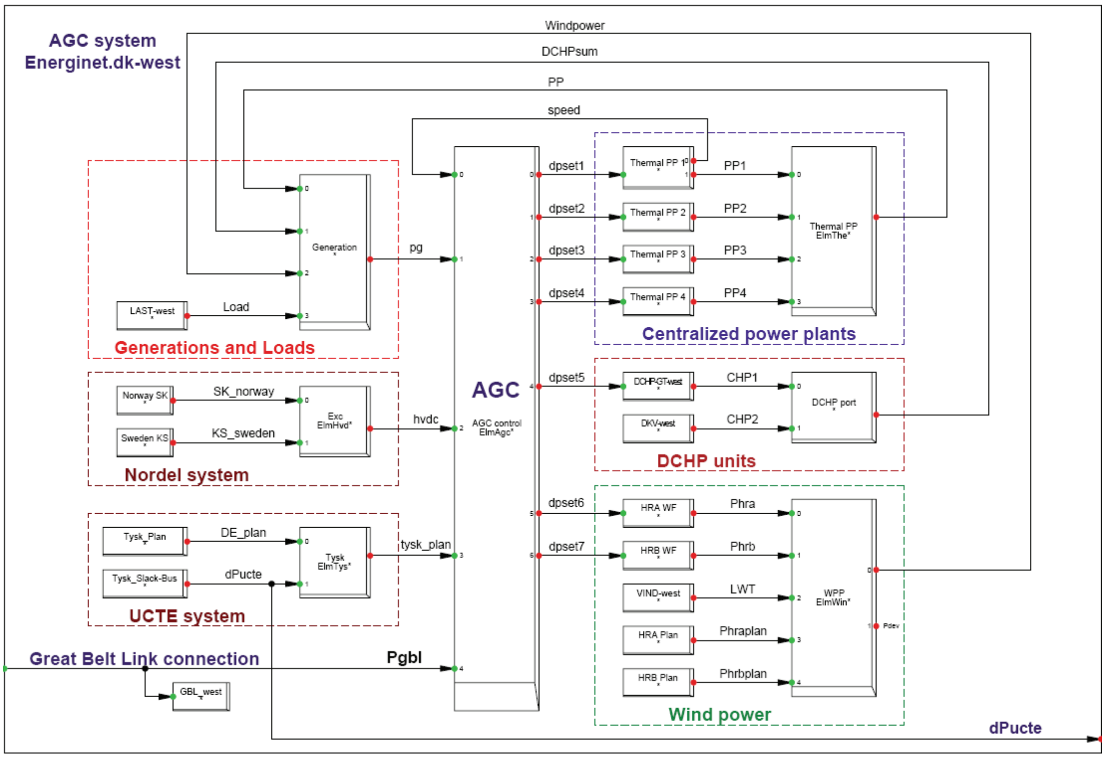


**Figure A-3. AGC system: Energinet.dk – west in 2007**

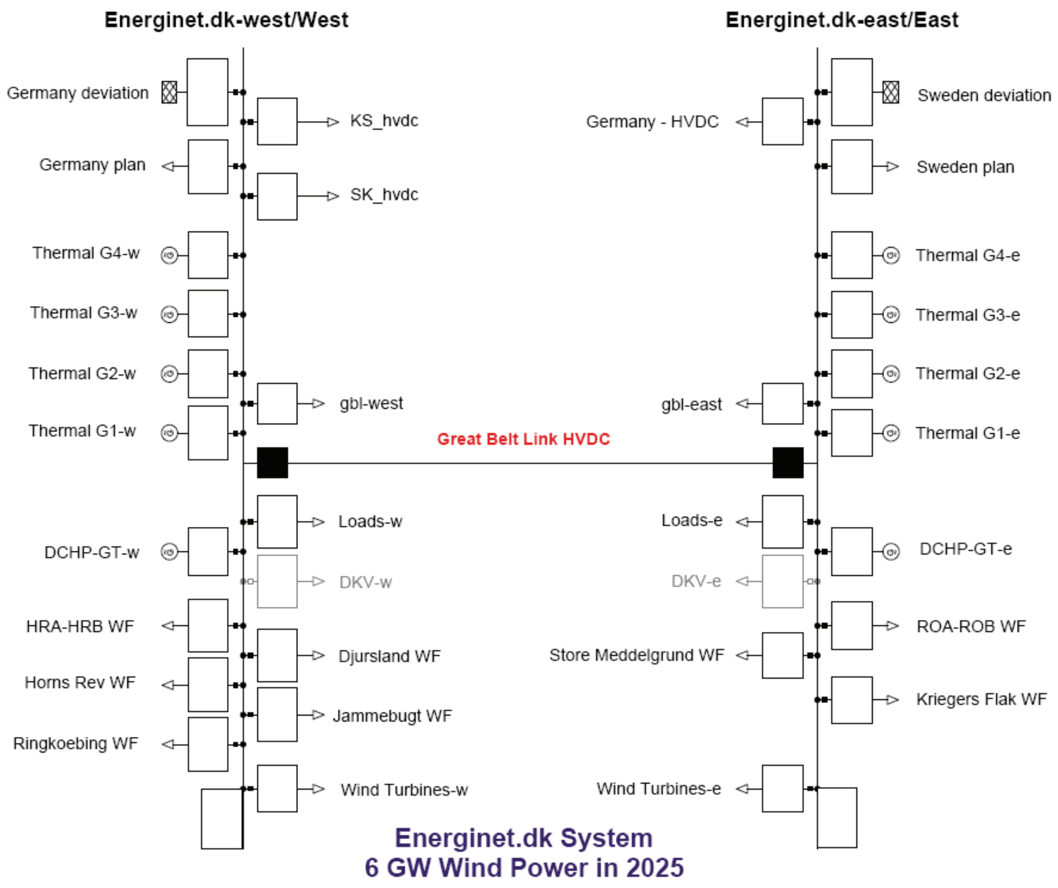


**Figure A-4. Energinet.dk – 2025**

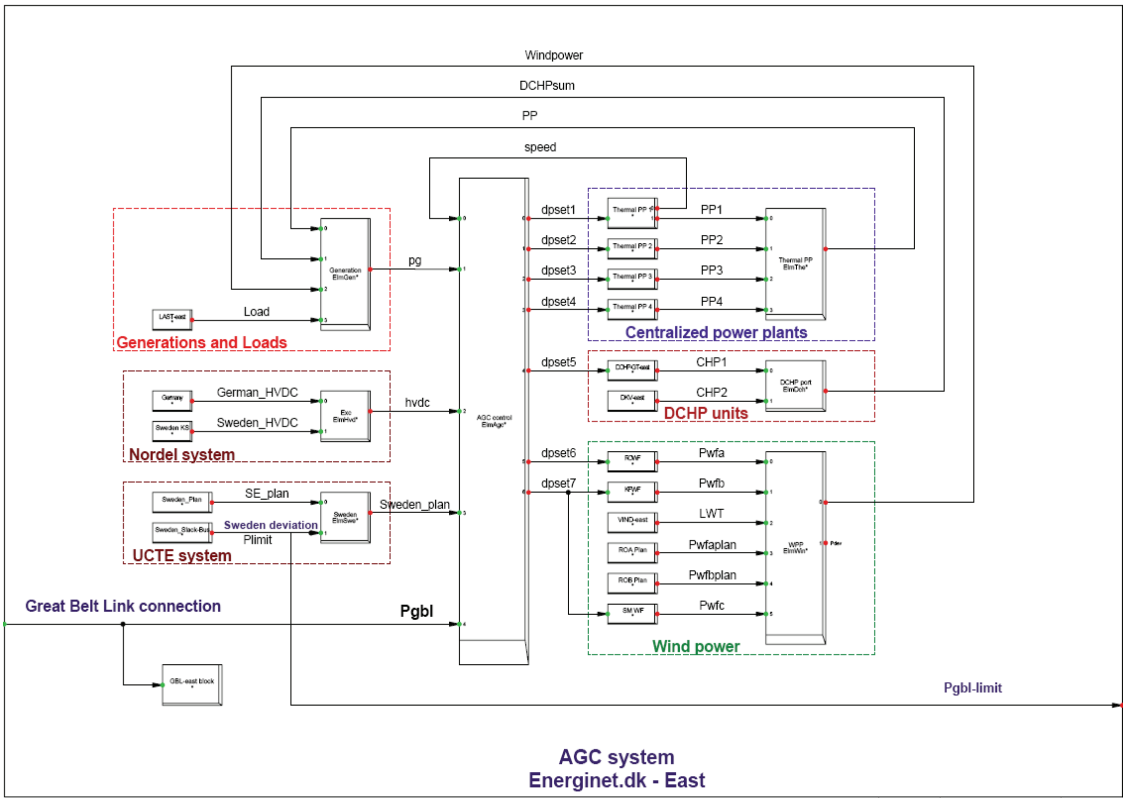


**Figure A-5. AGC system: Energinet.dk – east in 2025**

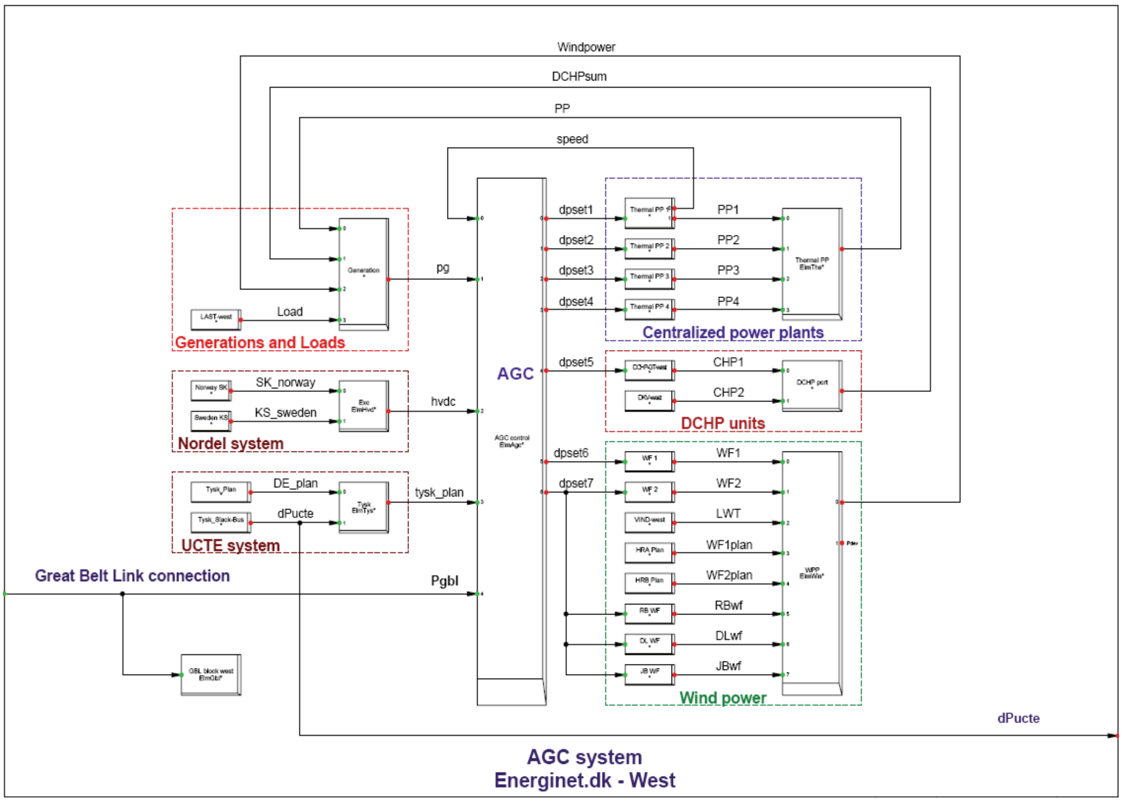


**Figure A-6. AGC system: Energinet.dk – west in 2025**

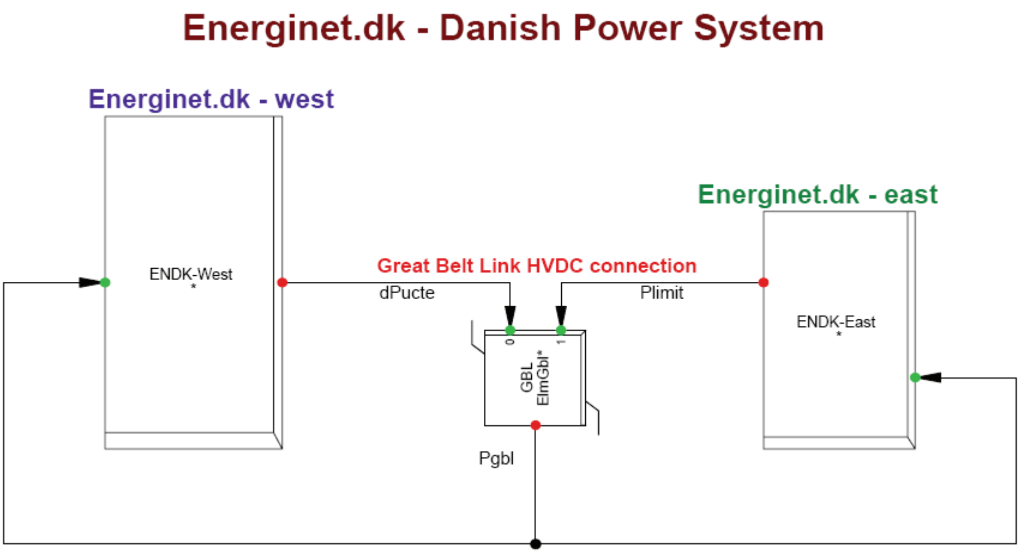


**Figure A-7. GBL connection**

## A.1 Centralized thermal power plant model

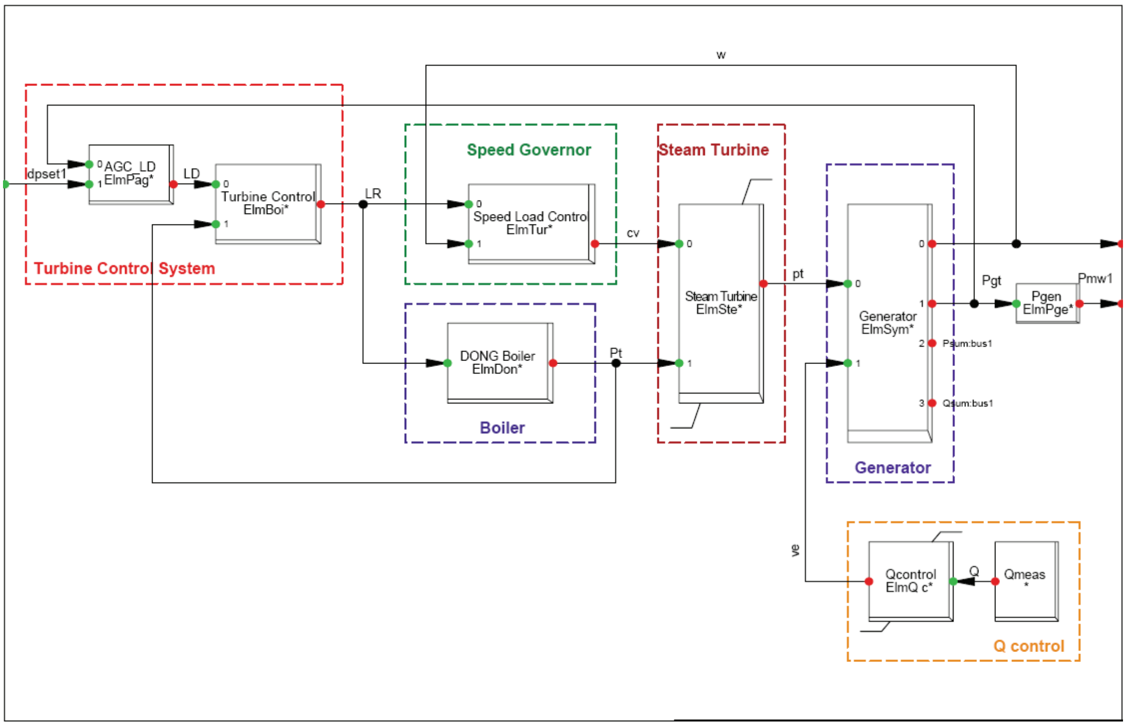


**Figure A-8. Thermal power plant model**

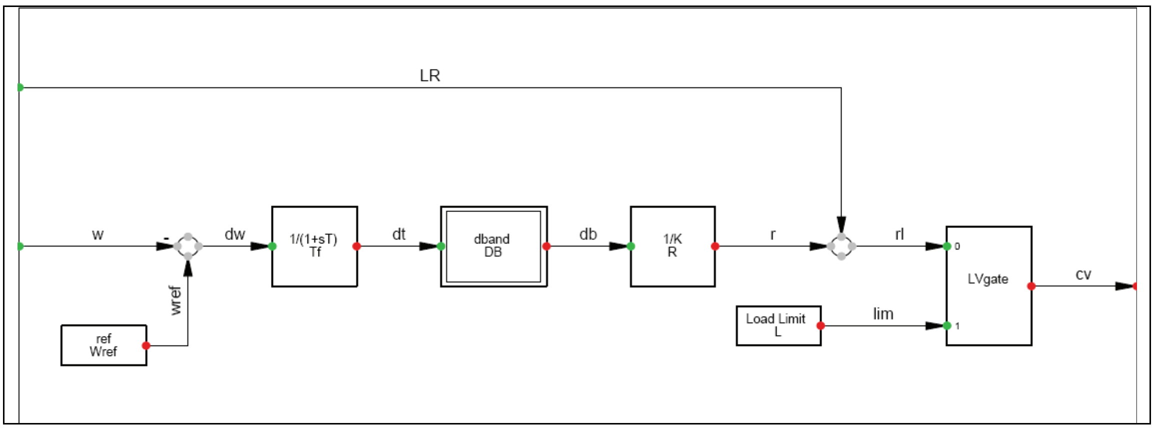


**Figure A-9. Speed governor model**

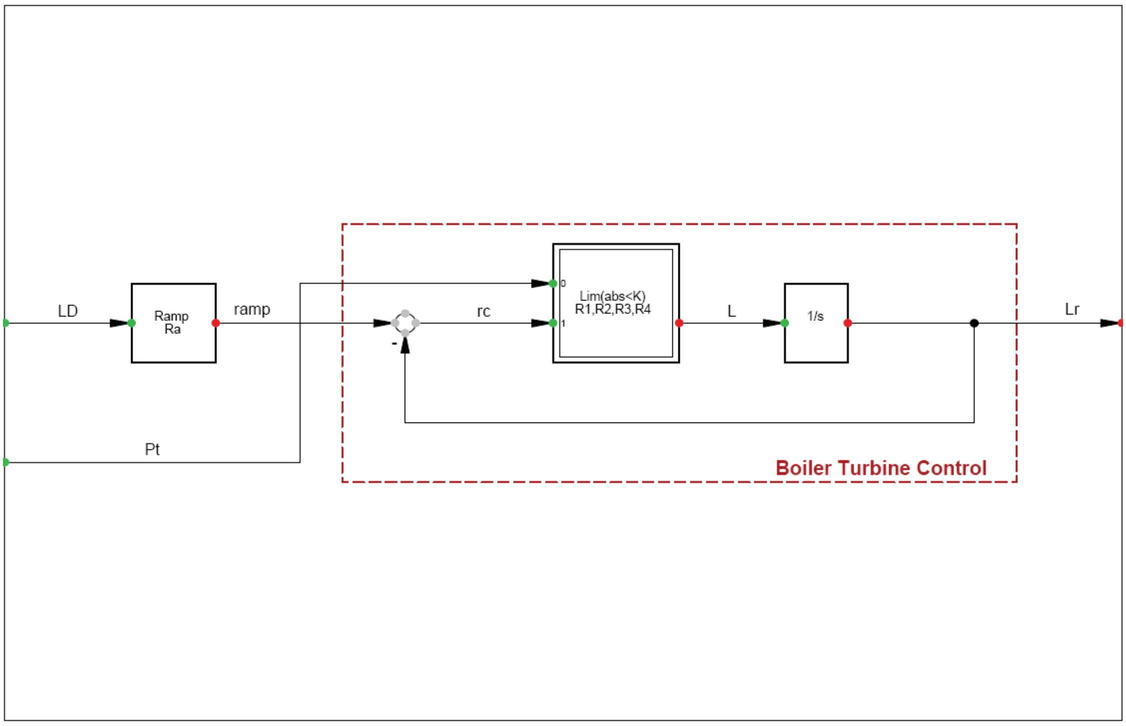


**Figure A-10. Boiler turbine control model**

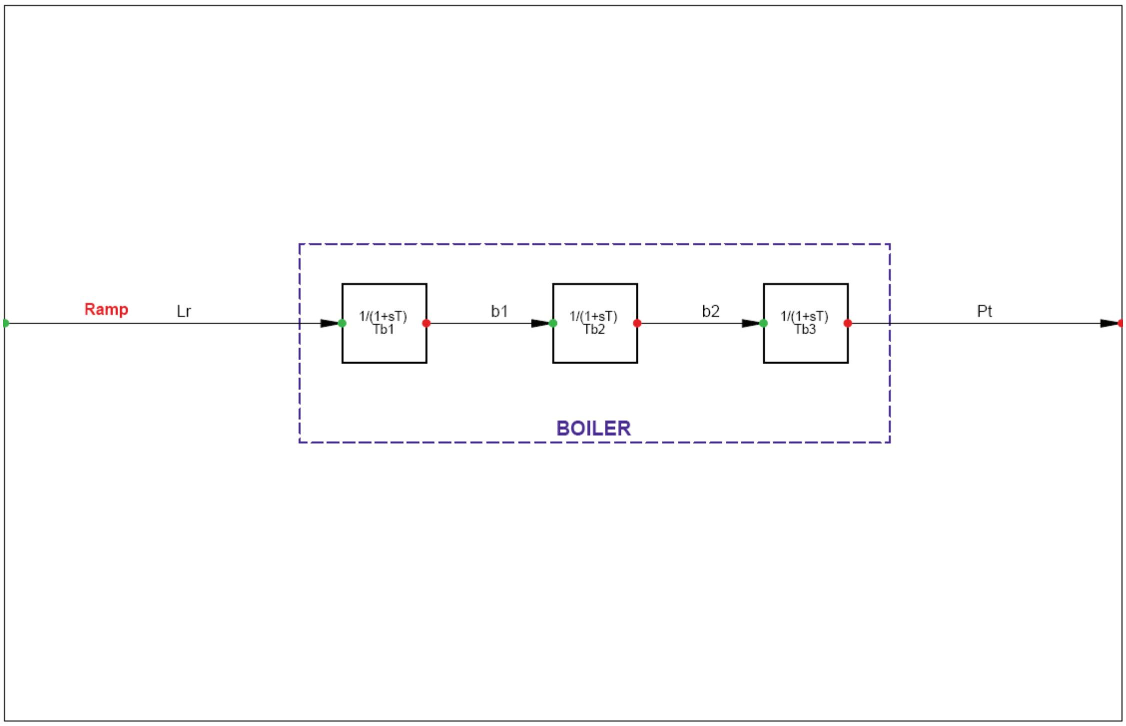


**Figure A-11. Boiler model**

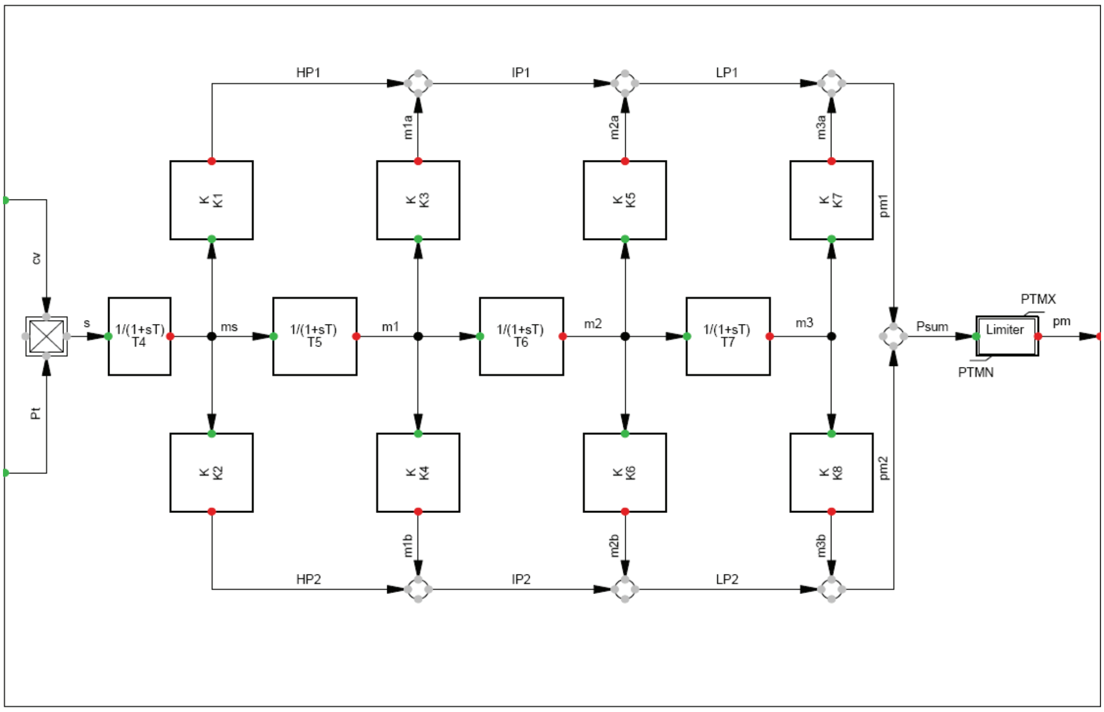


**Figure A-12. Steam turbine model**

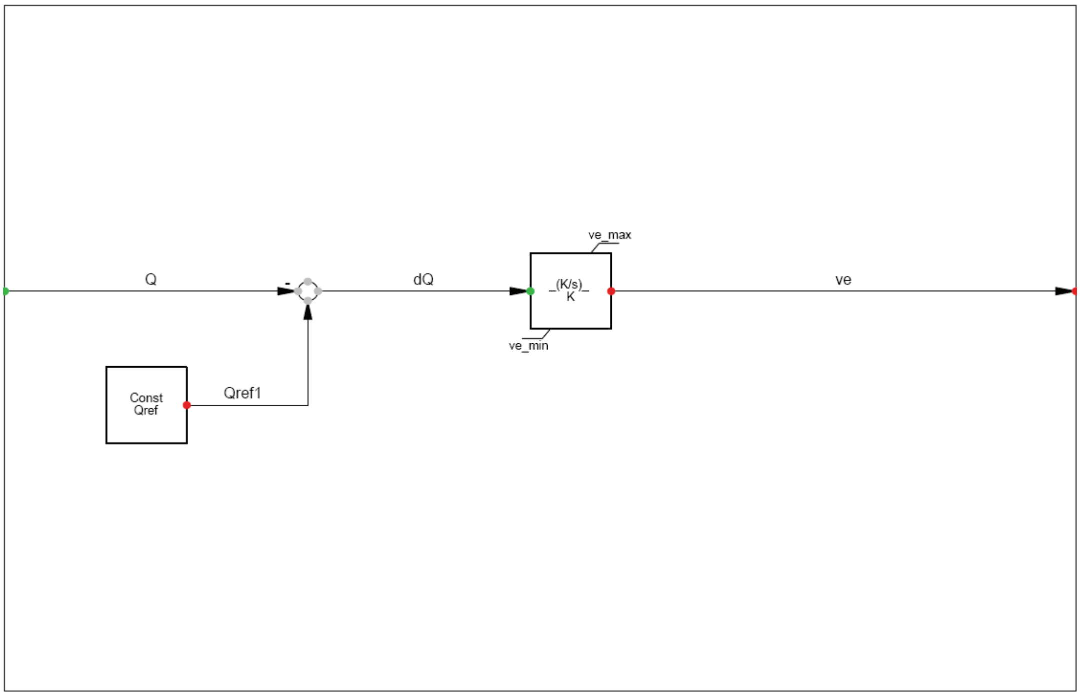


**Figure A-13. Reactive power control**

## A.2 DCHP unit model

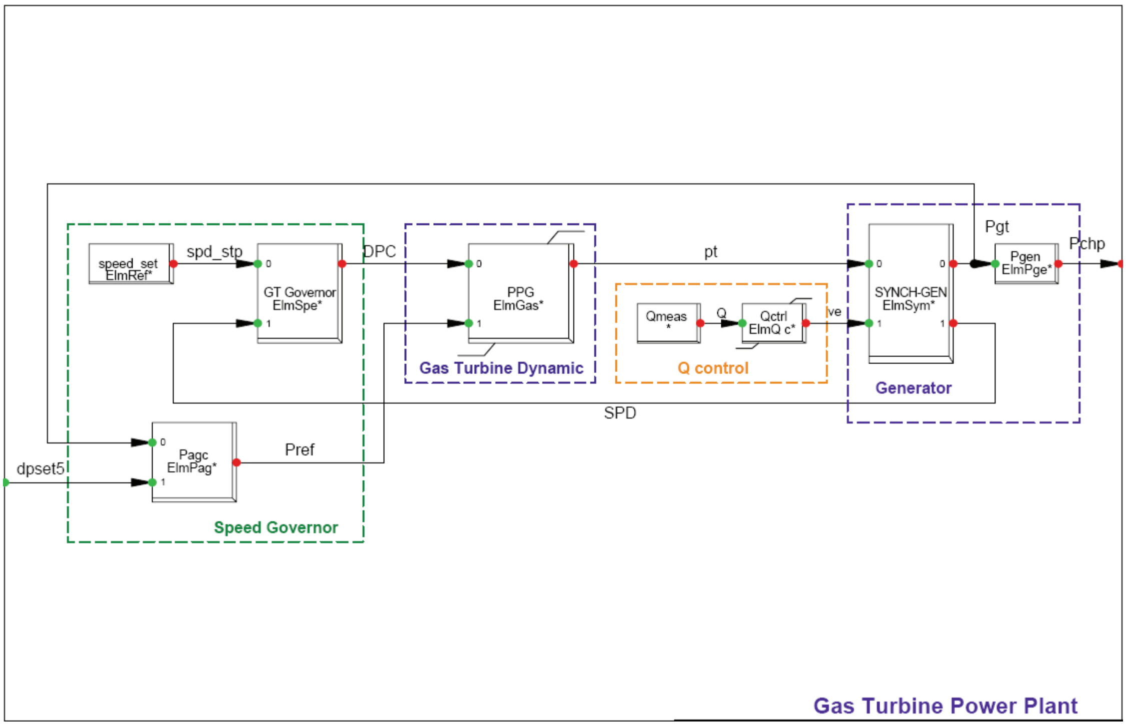


**Figure A-14. Decentralized CHP unit with gas turbine**

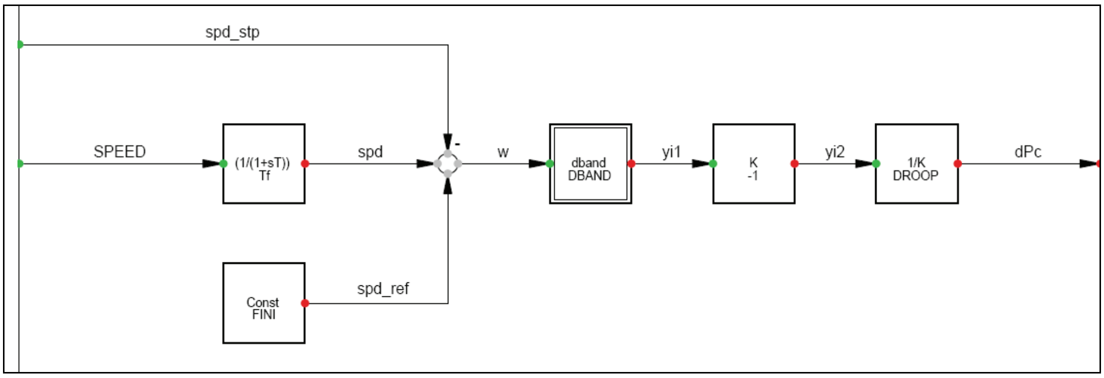


**Figure A-15. DCHP – speed governor**

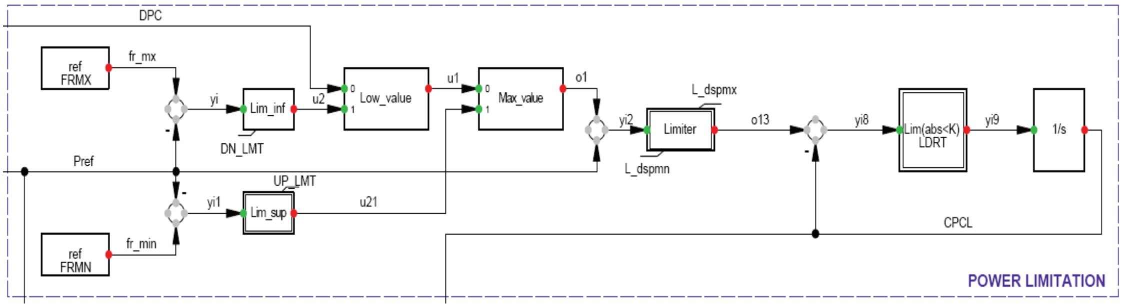


**Figure A-16. DCHP – power limitation**

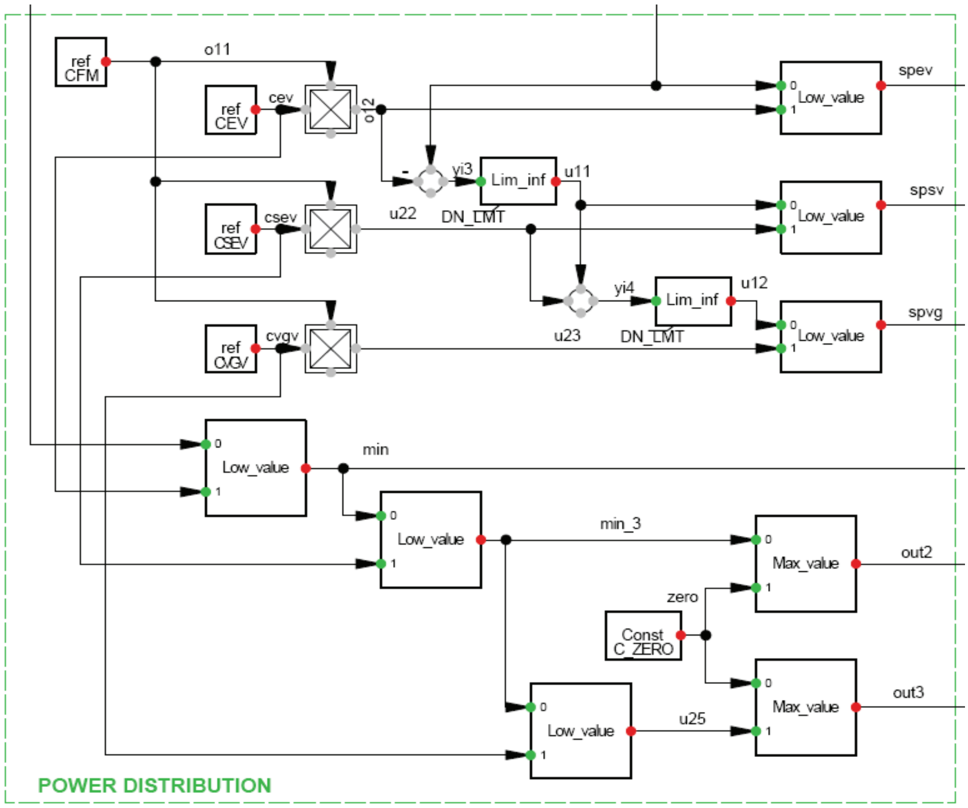


**Figure A-17. DCHP – power distribution**

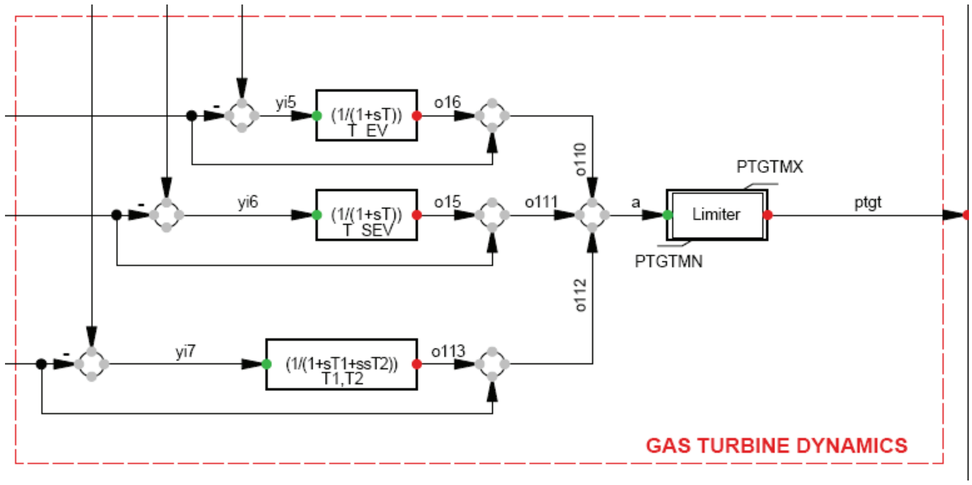


**Figure A-18. DCHP – gas turbine dynamics**

## A.3 Wind farm model

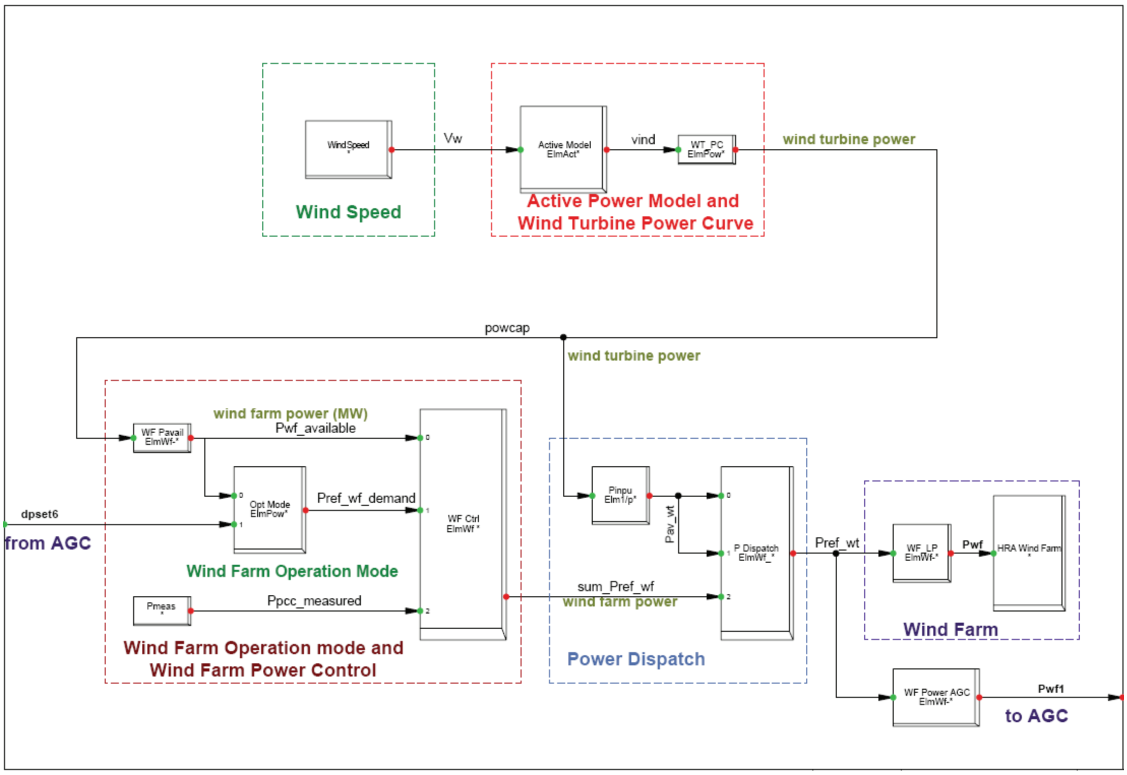


**Figure A-19. An aggregated wind farm model**

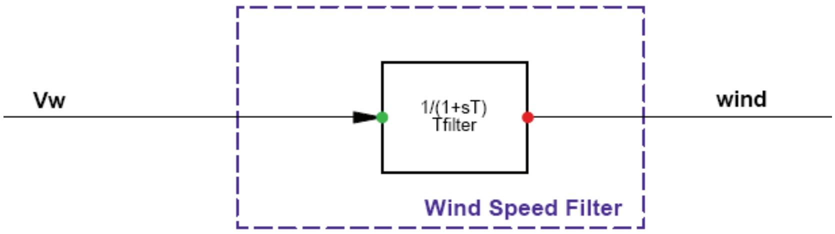


**Figure A-20. Active power model**

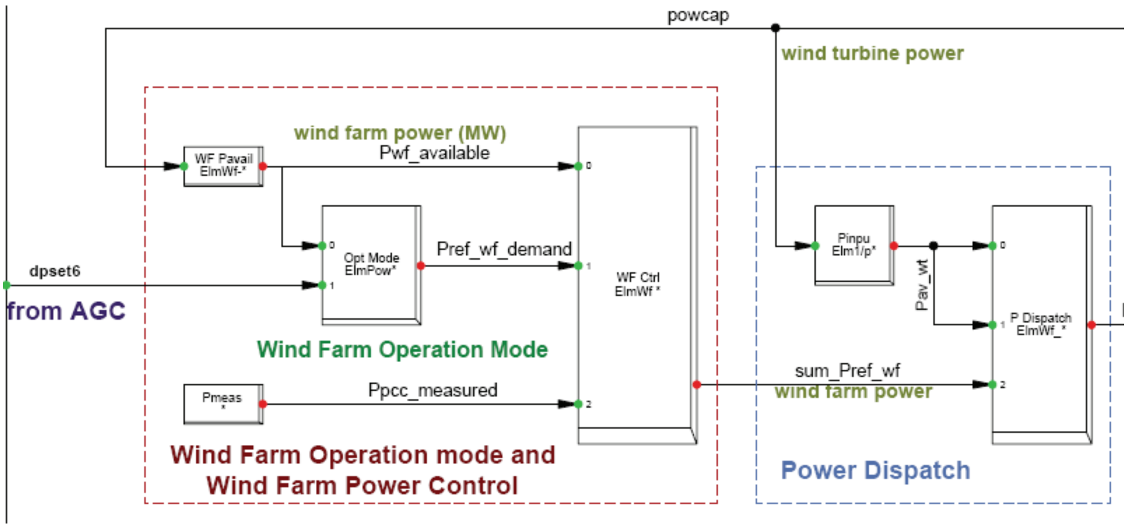


**Figure A-21. Wind farm controller and power dispatch**

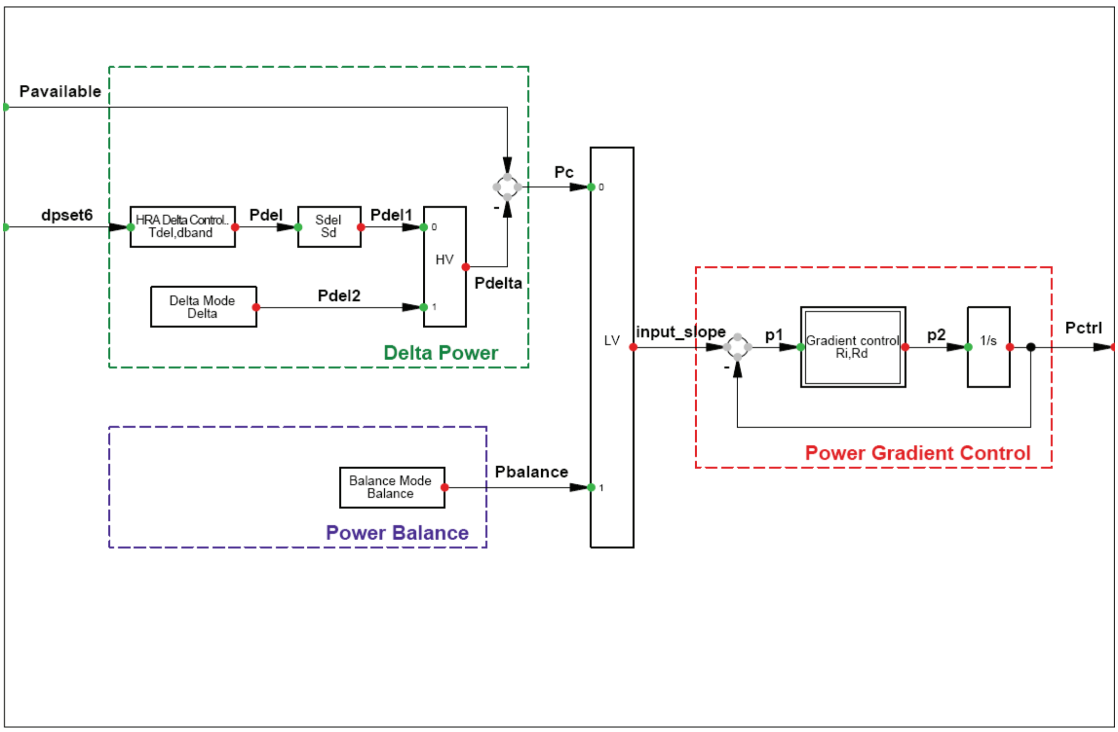


**Figure A-22. Wind farm operation mode (Opt Mode block)**

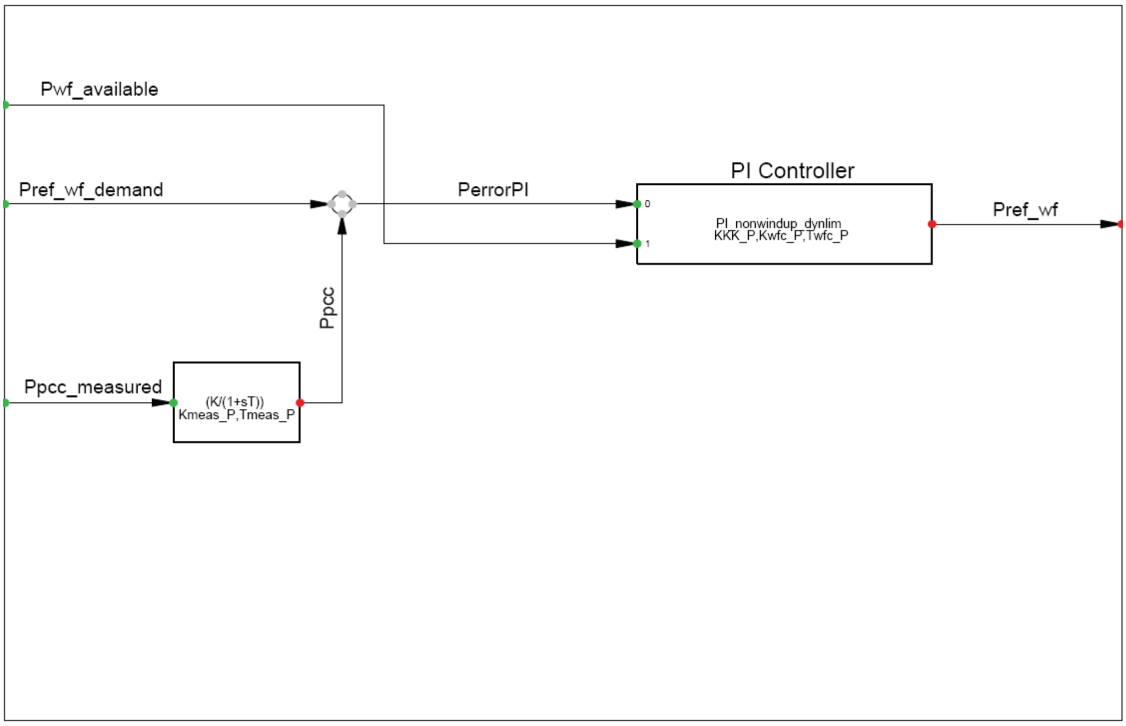


**Figure A-23. Wind farm power control (WF Ctrl block)**

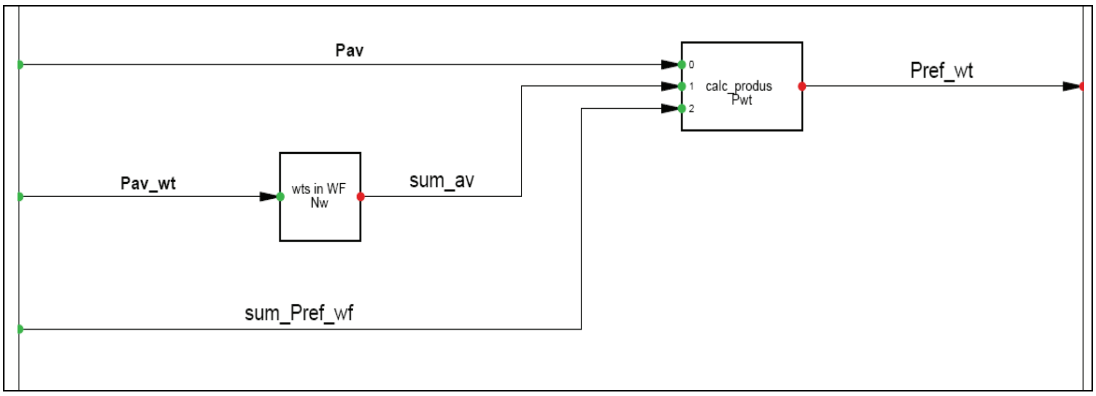


**Figure A-24. Power dispatch**

# B. Model parameters

Parameters of all models are presented in this Appendix as shown in the following tables. Parameters of the AGC system are shown in Table B-1. Parameters of a centralized thermal power plant are shown in Table B-2. Parameters of a DCHP unit model are shown in Table B-3. Parameters of the wind farm model are shown in Table B-4. Parameters of the great belt link HVDC connection model are shown in Table B-5.

**TABLE B-1**
**PARAMETERS OF AN AGC SYSTEM**

| Parameters | Description | Variable |
|---|---|---|
| $T_{AGC}$ | AGC time constant | 2 sec. |
| Dead band | AGC dead band | 2 MW |
| $F_{ref}$ | Reference frequency | 50 Hz. |
| R | Frequency bias | 0.005 |
| pf1 | Participation factor for power plant unit 1 | 0 - 1.0 |
| pf2 | Participation factor for power plant unit 2 | 0 - 1.0 |
| pf3 | Participation factor for power plant unit 3 | 0 - 1.0 |
| pf4 | Participation factor for power plant unit 4 | 0 - 1.0 |
| pf5 | Participation factor for DCHP unit | 0 - 1.0 |
| pf6 | Participation factor for wind farm 1 | 0 - 1.0 |
| pf7 | Participation factor for wind farm 2 | 0 - 1.0 |

**TABLE B-2**
**PARAMETERS OF AN AGGREGATED CENTRALIZED POWER PLANT**

| Parameters | Description | Variable |
|---|---|---|
| $T_{LR}$ | Load reference time constant | 1 sec. |
| R1* | Ramp rate: P <35% | MW/sec. |
| R2* | Ramp rate: 35% ≤ P < 50% | MW/sec |
| R3* | Ramp rate: 50% ≤ P < 90% | MW/sec |
| R4* | Ramp rate: P ≥ 90% | MW/sec |
| $T_g$ | Governor time constant | 1 sec. |
| Dead band | Frequency deadband in speed governor | 1 MW |
| Droop | Governor droop | 1 p.u. |
| $T_b$* | Boiler time constant | 100 sec. |
| $T_1$ | High pressure turbine bowl time constant | 10 sec. |
| $T_2$ | Reheater time constant | 25 sec. |
| $T_3$ | Crossover time constant | 5 sec. |
| $T_4$ | Double reheater time constant | 4 sec. |
| $K_1$ | Very high power turbine power fraction | 20 % |
| $K_2$ | Very high power turbine power fraction | 20% |
| $K_3$ | High power turbine power fraction | 10% |
| $K_4$ | High power turbine power fraction | 10% |
| $K_5$ | Intermediate power turbine power fraction | 10% |
| $K_6$ | Intermediate power turbine power fraction | 10% |
| $K_7$ | Low power turbine power fraction | 10% |
| $K_8$ | Low power turbine power fraction | 10% |
| PTMX | Maximum power output. | MW. |
| PTMN | Minimum power output | MW. |

* Parameters of ramp rate and boiler time constant of different thermal power plants are shown in Table 4-3 and Table 4-4 in Chapter 4.

**TABLE B-3**
**PARAMETERS OF AN AGGREGATED DECENTRALIZED CHP UNIT***

| Parameters | Description | Variable |
|---|---|---|
| $T_f$ | Pre-filter time constant | 0.5 sec. |
| $\omega_{ref}$ | Reference frequency | 50 Hz. |
| Dead band | Frequency deadband | 0.015 Hz. |
| Droop | Governor droop | 0.1 p.u. |
| $FR_{max}$ | Maximum power level for frequency response | 1.0 p.u. |
| $FR_{min}$ | Minimum power level for frequency response | 0.4 p.u. |
| $L_{max}$ | Maximum load set point | 1.0 p.u. |
| $L_{min}$ | Minimum load set point | 0.4 p.u. |
| Rate | Ramp rate | 0.1 p.u./sec. |
| CFM | Base load function | 1 sec. |
| CEV | Environmental burner capacity | 0.15 sec. |
| CSEV | Sequential environmental burner capacity | 0.25 sec. |
| CVGV | Variable inlet guide vane position compressor capacity | 0.6 sec. |
| $\omega$ | Un-damped natural frequency | 0.22 rad/sec. |
| $\zeta$ | Damping ratio of the compressor | 0.8 p.u. |
| $T_{EV}$ | Environmental burner dynamic time constant | 5 sec. |
| $T_{SEV}$ | Sequential environmental burner dynamic time constant | 5 sec. |
| $P_{max}$ | Maximum power output | 1.1 p.u. |
| $P_{min}$ | Minimum power output | 0.0 p.u. |

* Parameters of DCHP unit is based on the model of Alstom GT 26, can be found in [26]

**TABLE B-4**
**PARAMETERS OF AN AGGREGATED WIND FARM MODEL**

| Parameters | Description | Variable |
|---|---|---|
| $T_f$ | Filter time constant | 7 sec. |
| $P_G$ | Power gradient control | 10 MW/min. |
| $K_D$ | Delta mode switch | 1 sec. |
| $P_{Delta}$* | Delta control. | 0 MW* |
| $P_{Balance}$* | Balance control | Rated power in MW* |
| $K_W$ | Gain measured power. | -1 |
| $T_W$ | Measured power time constant | 0.2 sec. |
| $K_P$ | Power gain of the controller | 100 |
| $K_I$ | Power gain at the controller | 0.01 |
| $T_I$ | Controller time constant | 0.01 sec. |
| $P_R$* | Rated power of wind turbine in a wind farm | MW** |
| N | Number of wind turbines in a wind farm | Unit(s) |

* A wind farm will be operated at its maximum available power when $P_{Delta}$ is set to 0 MW and $P_{Balance}$ is set to the wind farm rated power

** Rated power of each wind farm are shown in Table 8-1 and Table 8-4

**TABLE B-5**
**PARAMETERS OF GREAT BELT LINK POWER CONTROLLER**

| Parameters | Description | Variable |
|---|---|---|
| $T_{GBL}$ | 1 sec. | 1 sec. |
| $R_{max}$ | Maximum rate limiter | 16.65 MW/sec. |
| $R_{min}$ | Minimum rate limiter | 0.0167 MW/sec. |
| Dead band | GBL power deadband | 18 MW |
| $P_{max}$ | Maximum power | 600 MW |
| $P_{Limit}$ | GBL power limit, based on the power transaction between ENDK-east and Sweden | 1300 MW* |

* This parameter can be changed; it is set to this value for all study case.

# C. Simulation results

## C.1 Simulations in chapter 7

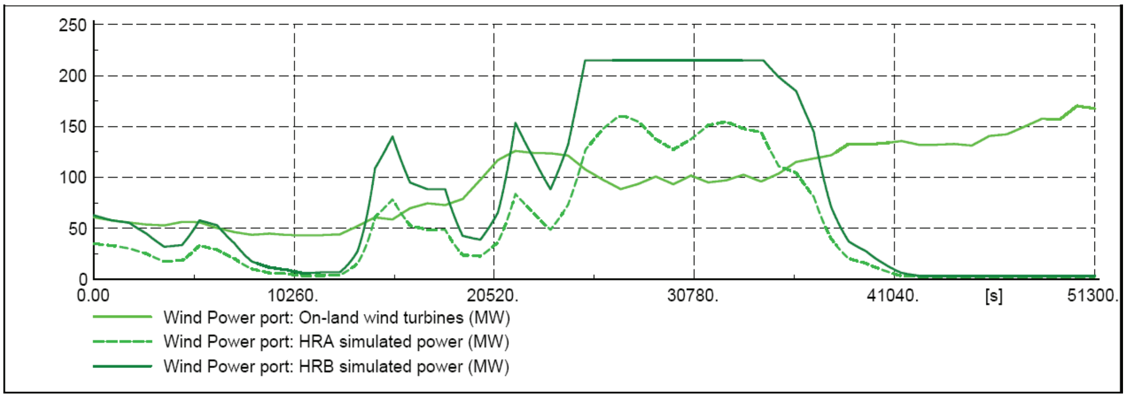


**Figure C-1. Wind power generations from on-land wind turbines, HRA wind farm and HRB wind farm in 7.4.1, 7.4.2 and 7.4.3**

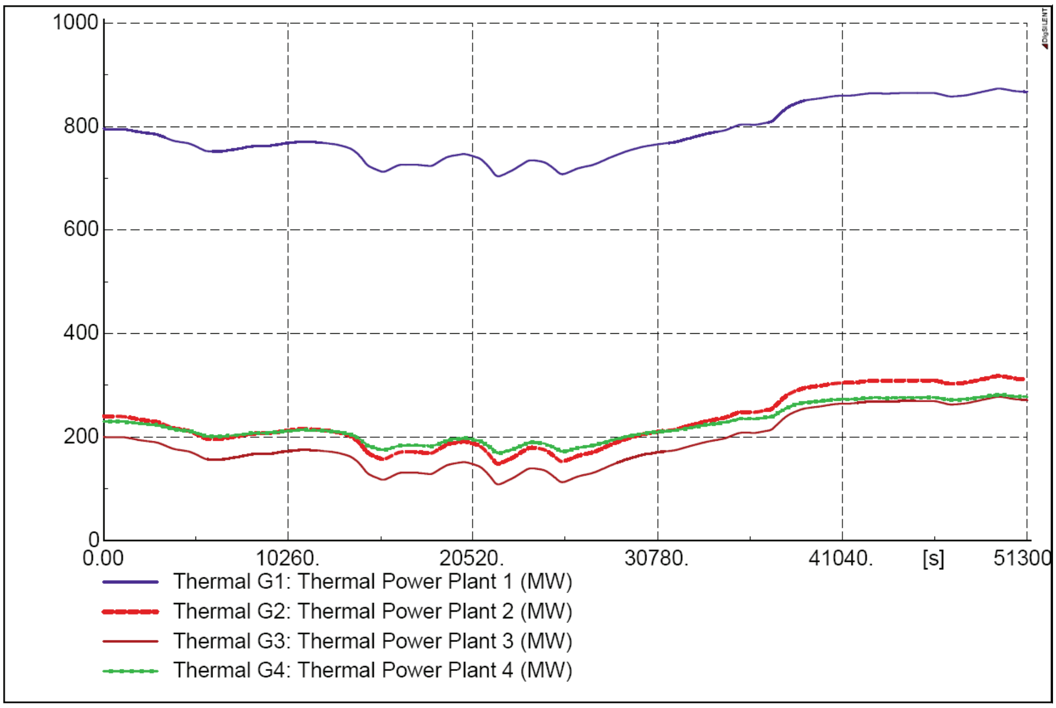


**Figure C-2. Power generations from centralized power plants of case 1 in 7.4.2**

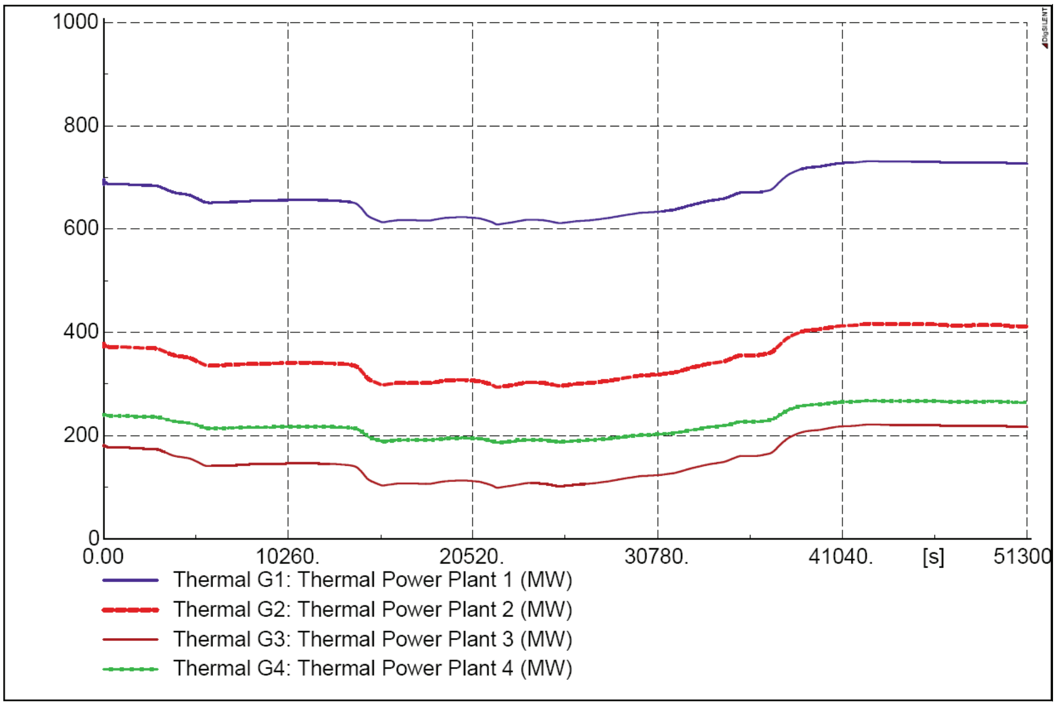


**Figure C-3. Power generations from centralized of power plants case 2 in 7.4.2**

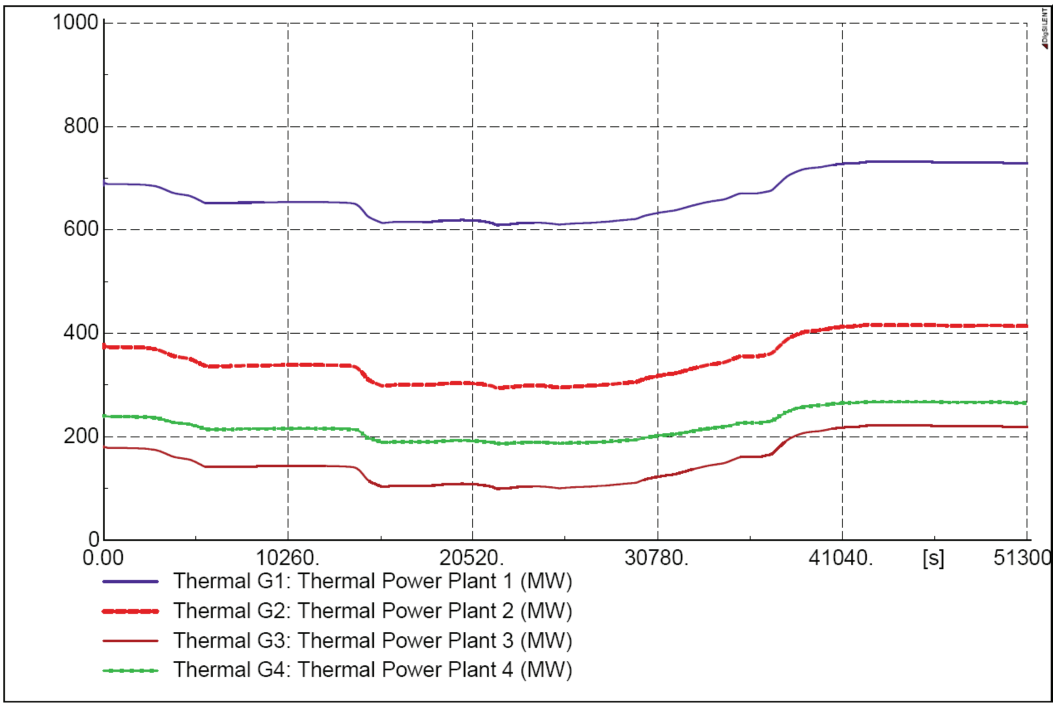


**Figure C-4. Power generations from centralized power plants of case 3 in 7.4.2**

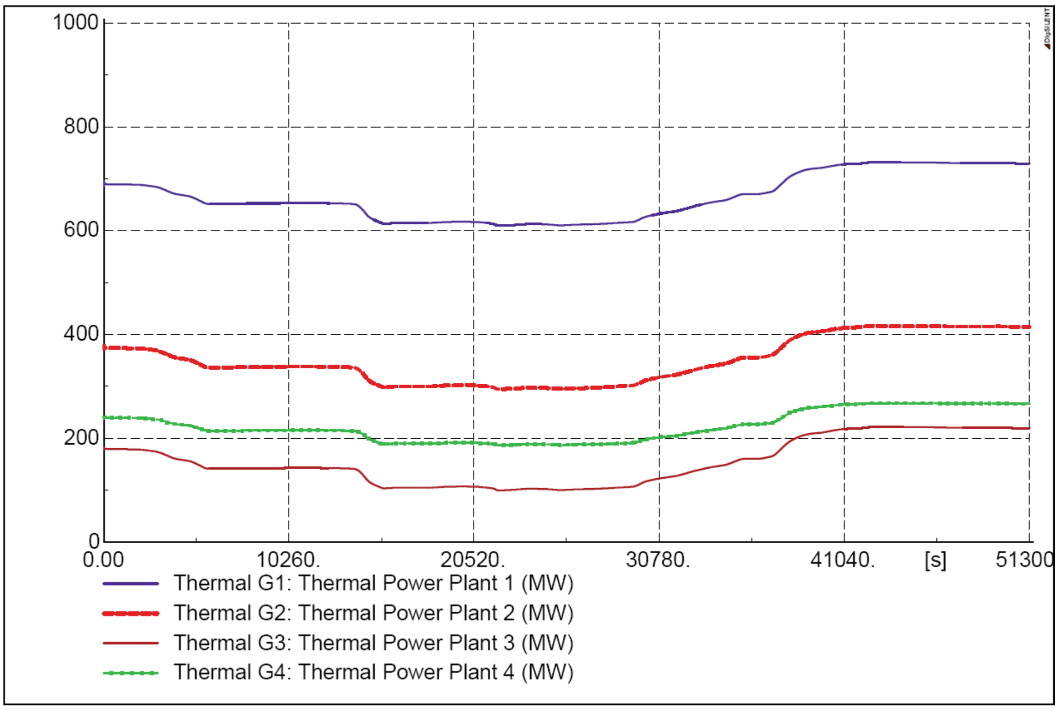


**Figure C-5. Power generations from centralized power plants of case 4 in 7.4.2**

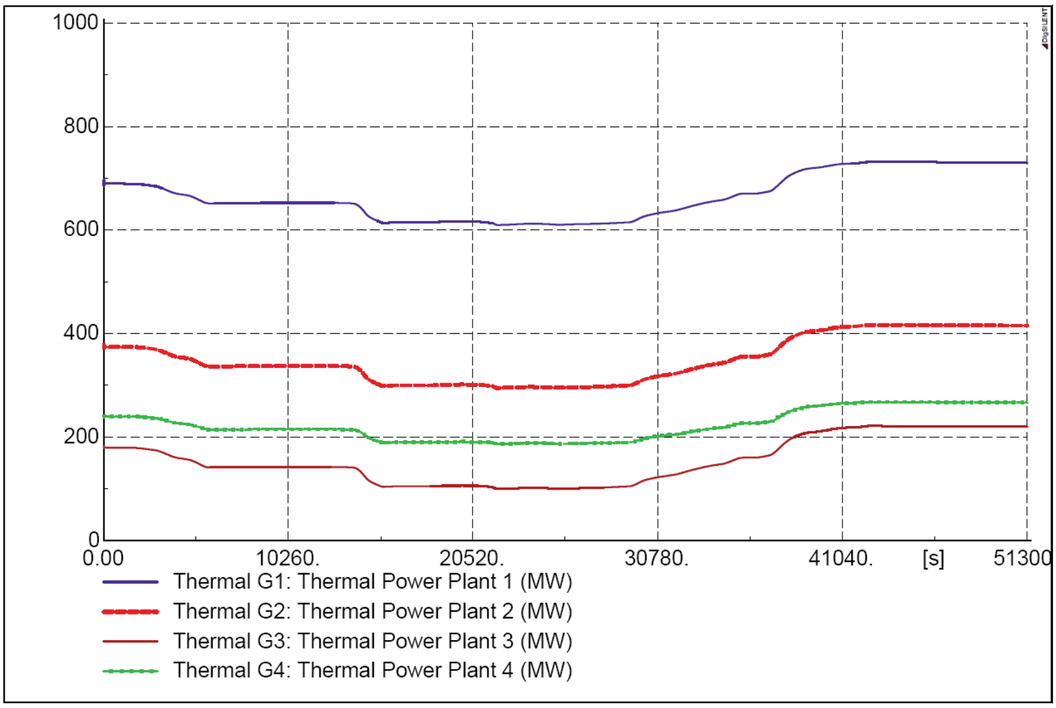


**Figure C-6. Power generations from centralized power plants of case 5 in 7.4.2**

## C.2 Simulations in chapter 8

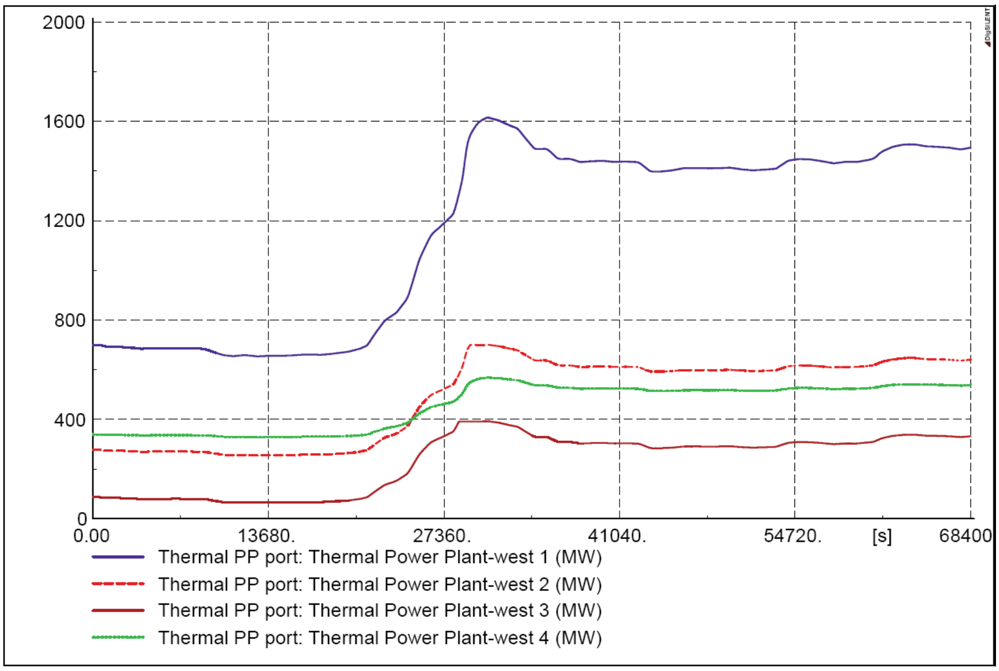


**Figure C-7. Power generations from centralized power plants in 8.2.1**

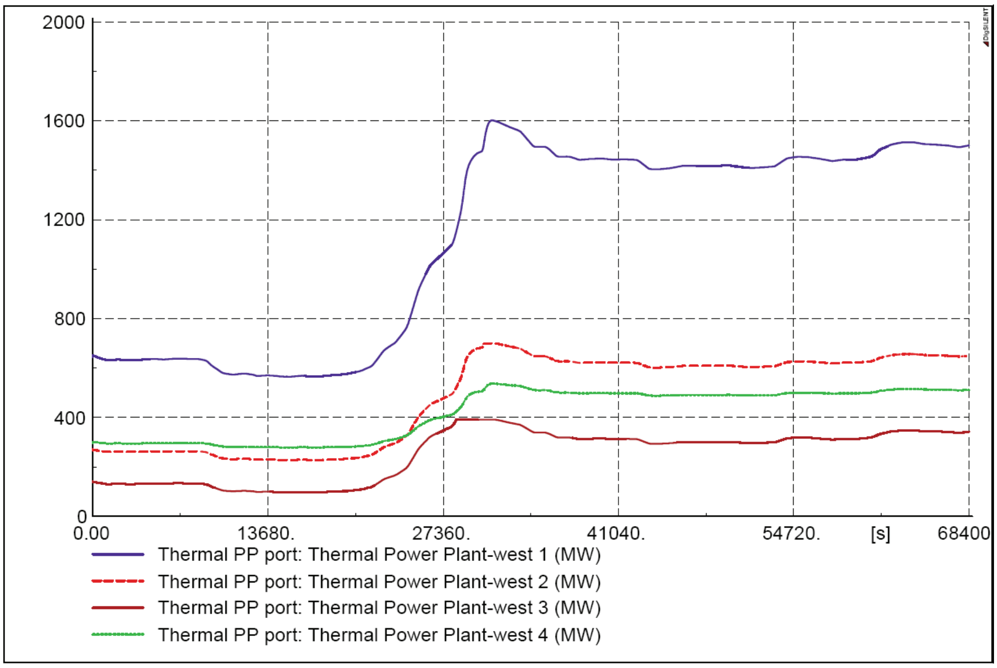


**Figure C-8. Power generations from centralized power plants in 8.2.2**

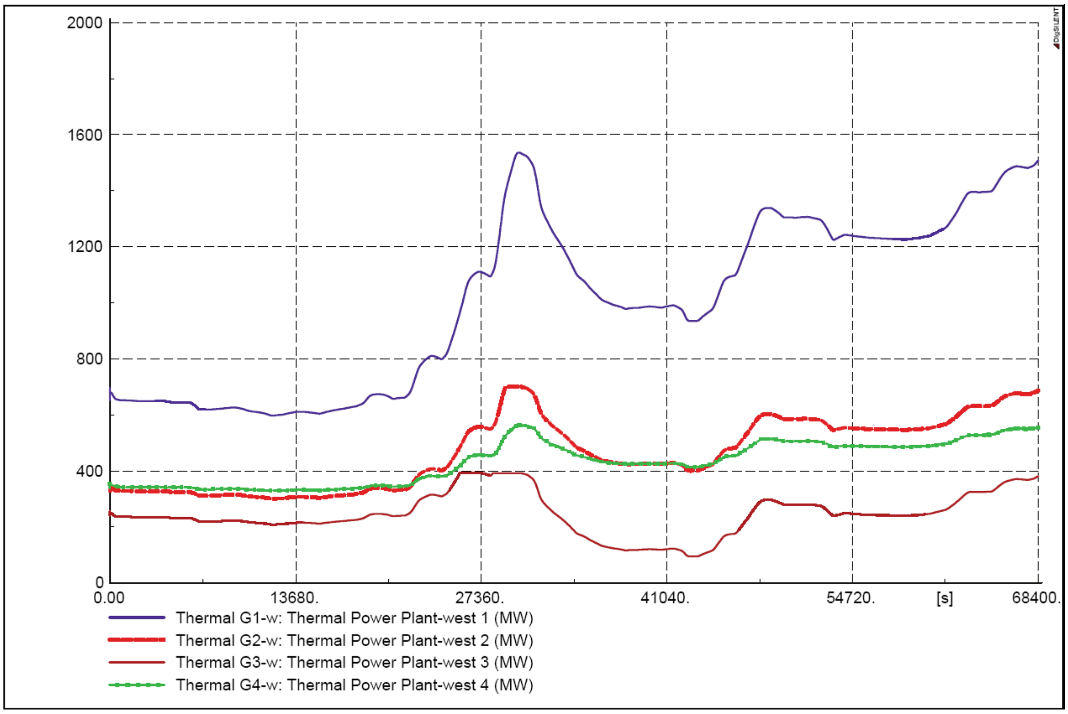


**Figure C-9. Power generations from centralized power plants in 8.3.1**

## C.3 Simulation results of system analysis in 2025 (section 8.3.2)

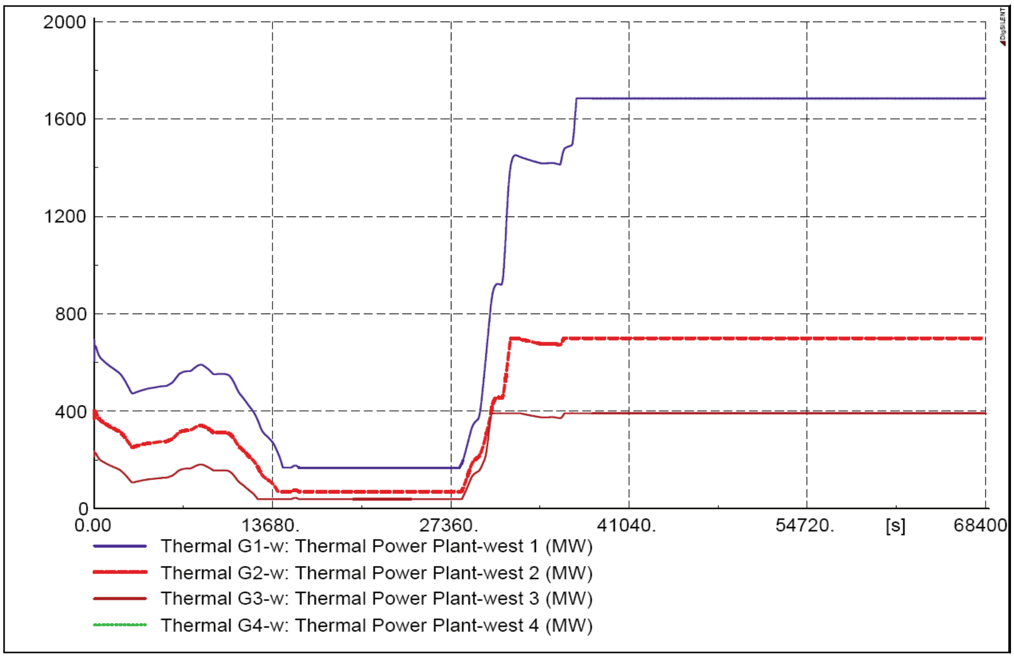


**Figure C-10. Power generations from centralized power plants in ENDK-west without the GBL**

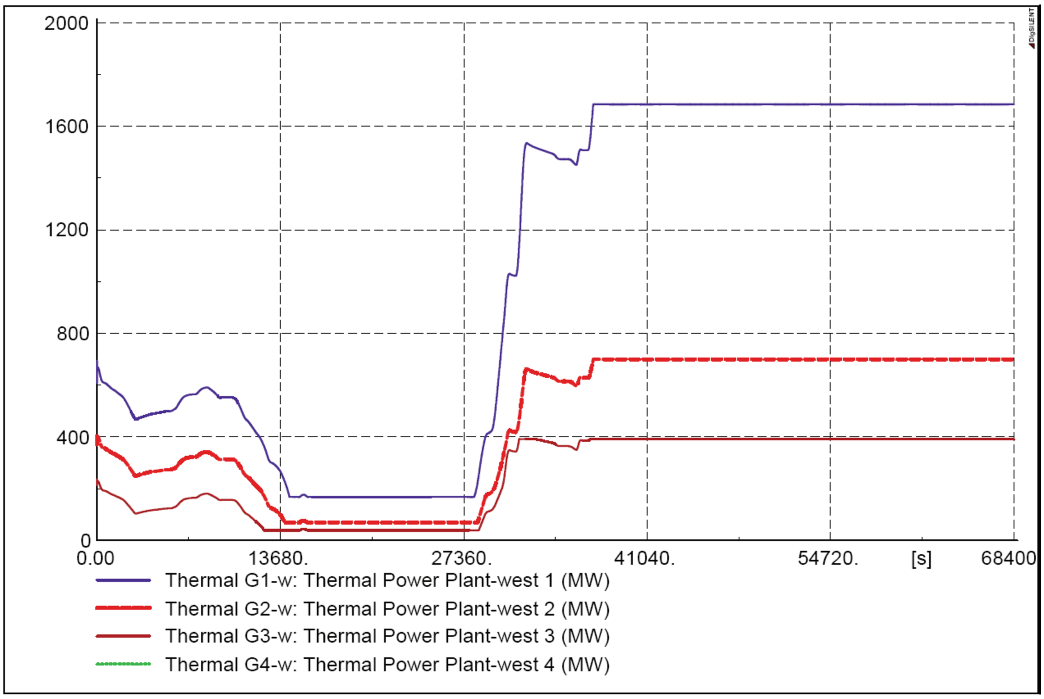


**Figure C-11. Power generations from centralized power plants in ENDK-west with the GBL**

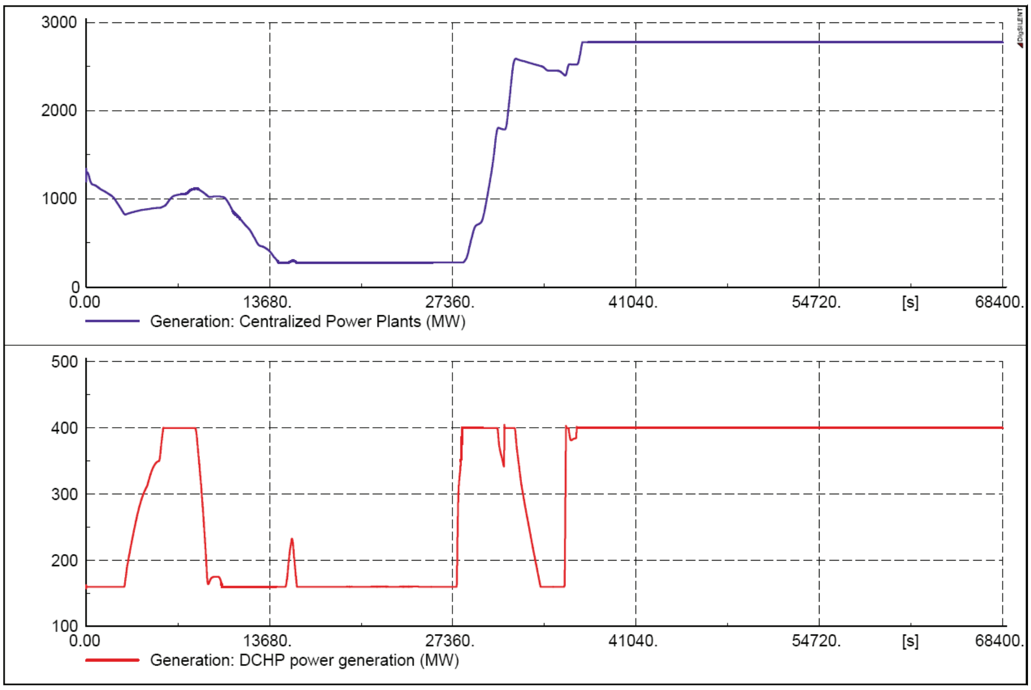


**Figure C-12. Power generations from centralized power plants in ENDK-west with the GBL**

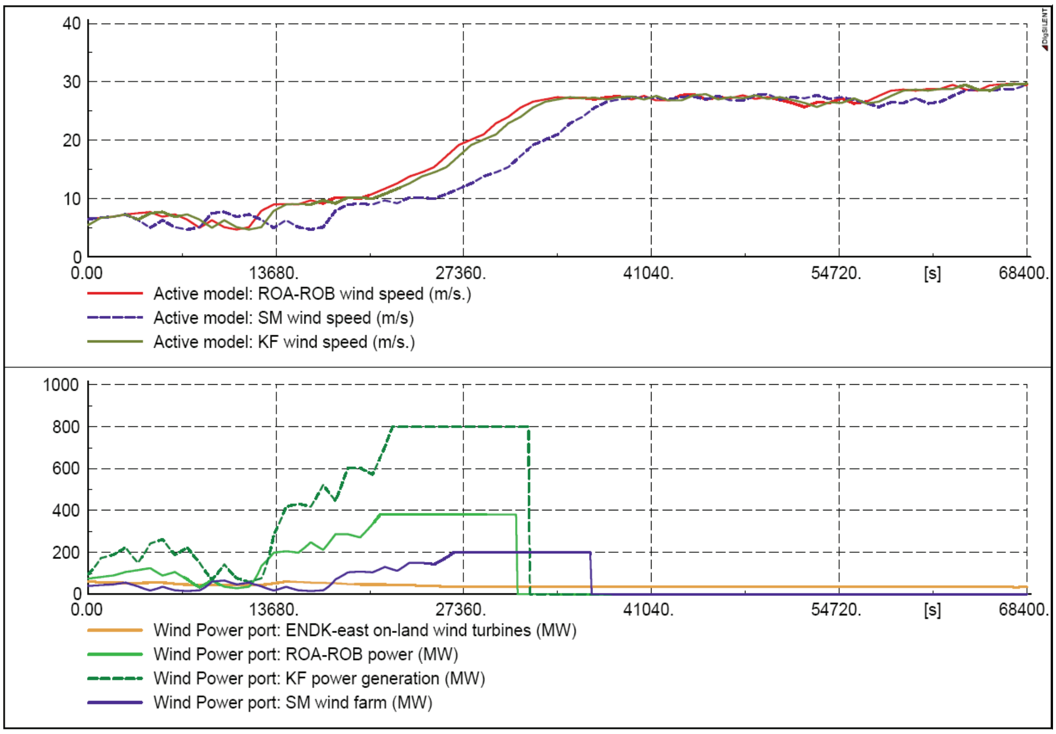


**Figure C-13. Wind power generations in Energinet.dk-east**

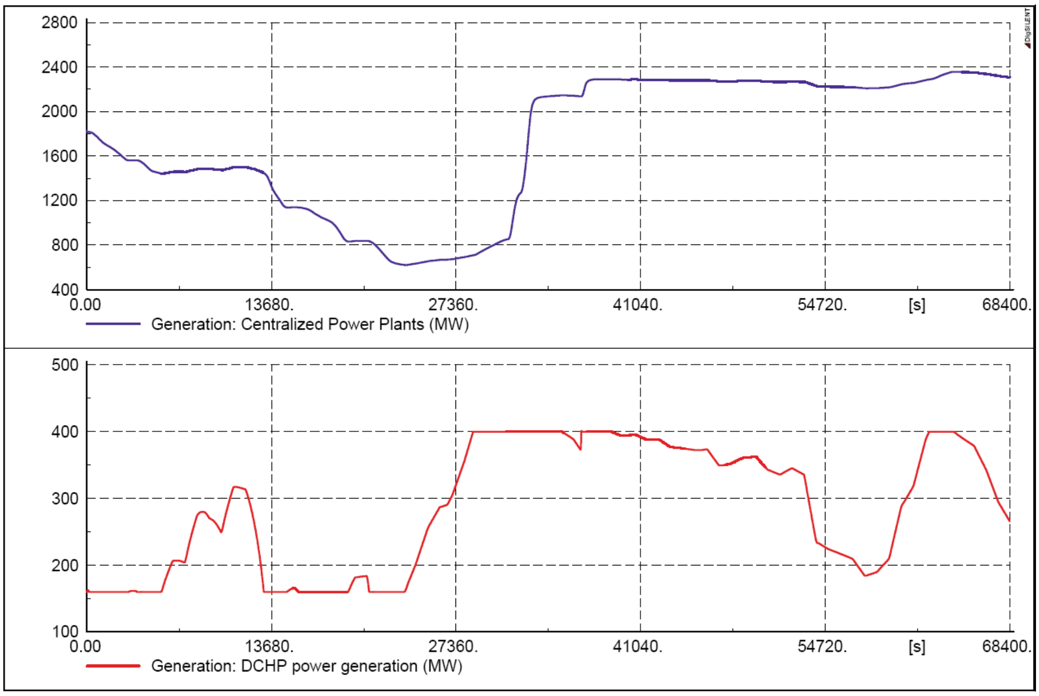


**Figure C-14. Power generations from centralized power plants in ENDK-east without the GBL**

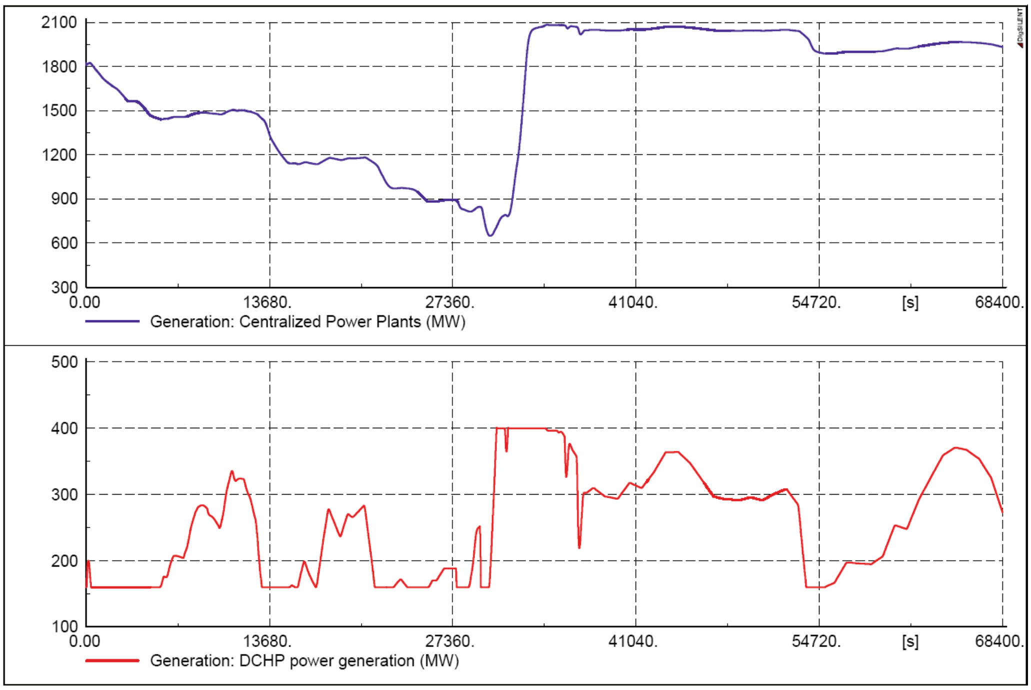


**Figure C-15. Power generations from centralized power plants in ENDK-east with the GBL**

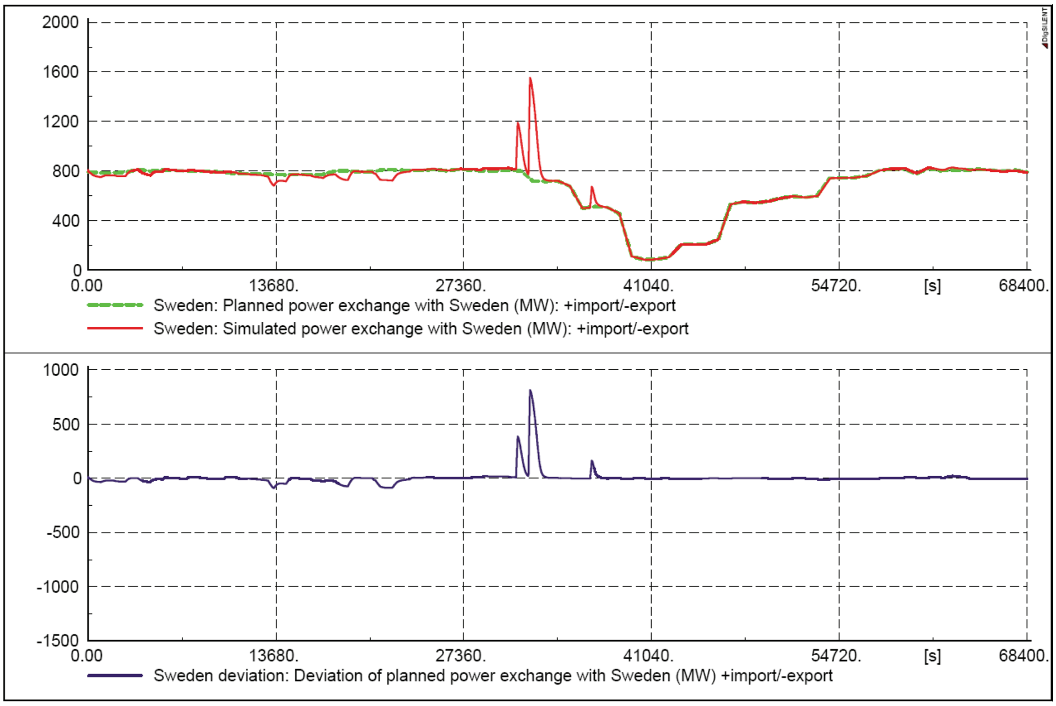


**Figure C-16. Deviation from plan between ENDK-east and Sweden without the GBL**

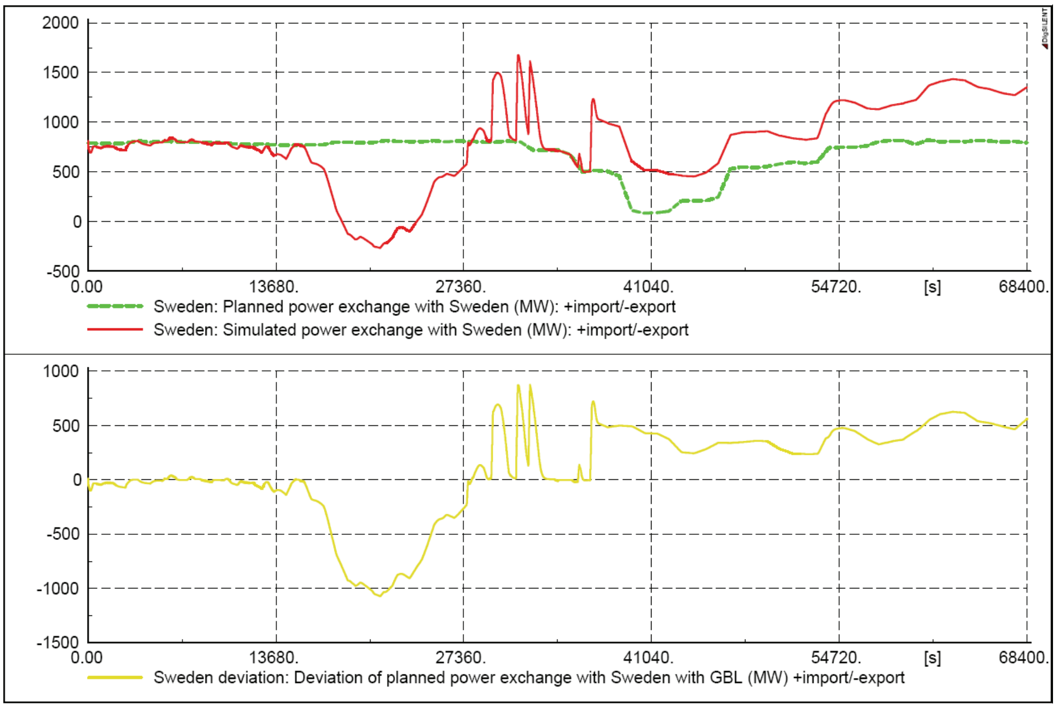


**Figure C-17. Deviation from plan between ENDK-east and Sweden with the GBL**

# List of Symbol and Abbreviation

| | |
|---|---|
| AC | Alternate Current |
| AGC | Automatic Generation Control |
| CHP | Combined Heat and Power |
| DCHP | Decentralized Combined Heat and Power |
| DFIG | doubly-fed induction generators |
| ENDK-east | Energinet.dk-east |
| EBDK-west | Energinet.dk-west |
| ETF | Equivalent Transfer Function |
| GBL | Great Belt Link |
| GCE | Generation Control Error |
| GCR | Grid Code Requirement |
| GRC | Generation Rate Constraint |
| GW | Giga Watt |
| HRA | Horns Rev A wind farm |
| HRB | Horns Rev B wind farm |
| HVDC | High Voltage Direct Current |
| HVDC-VSC | High Voltage Direct Current – Voltage Source Converter |
| km | Kilometre |
| kV | Kilo volt |
| LFC | Load Frequency Control |
| min | Minute |
| MW | Mega Watt |
| PCC | Point of common coupling |
| *pf* | participation factor |
| ROA | Rødsand A wind farm |
| ROB | Rødsand B wind farm |

| | |
|---|---|
| SCADA system | Supervisory Control And Data Acquisition system |
| SCIG | squirrel-cage induction generators |
| t | Time variable (second) |
| TSO | Transmission System Operator |
| TWh | Tera Watt hour |
| UCTE | Union for the Coordination of Transmission of Electricity |

# List of Publications


1) A. Suwannarat, B. Bak-Jensen and Z. Chen, Power System Balancing with Large Scale Wind Power Integration, *Sixth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms*, Delft, The Netherlands, Oct. 2006

2) A. Suwannarat, B. Bak-Jensen, and Z. Chen, "Power System Stability with Large-Scale Wind Power Penetration", *IASTED AsiaPES 2007 Conference*, Phuket, April 2007

3) A. Suwannarat, B. Bak-Jensen, Z. Chen, H. Nielsen, J. Hjerrild, P. Sørensen, and A. D. Hansen, "Power System Operation with Large-Scale Wind Power Penetration", *IEEE Power Tech 2007 Conference*, Lausanne, July 2007

4) A. Suwannarat, B. Bak-Jensen, Z. Chen, H. Nielsen, J. Hjerrild, P. Sørensen, and A. D. Hansen, "Power Balancing Control with Large-Scale Wind Power Penetration in Denmark", *IASTED EuroPES 2007 Conference*, Palma de Mallorca, August 2007

5) R. Villafafila, A. Sumper, A. Suwannarat, B. Bak-Jensen, R. Ramirez, O. Gomis, and A. Sudria, "On wind power integration into electrical power system: Spain vs. Denmark", *9th Electrical Power Quality and Utilization International Conference (EPQU 2007)*, Barcelona, October 2007

# Resume

With wind power capacities increasing, the Danish TSO is faced with new challenges related to the uncertain nature of wind power. The fluctuating nature of wind power introduces several challenges to reliable power system operation and contributes to deviations in the planned power generation which can lead to power system control and balancing problems. In order to analyze the effects resulting from the structural changes in power generation and system operation by the penetration of large scale wind farms, the project “Integration and Control of Wind Farm in the Danish Electricity System” is set up. This project is made jointly between the Institute of Energy Technology; Aalborg University, DONG Energy, RISØ national laboratory, Vattenfall, and Energinet.dk, and funded by the 2004 – PSO – programme.

This PhD thesis is concerned with understanding, modelling, analyzing and mitigating long-term power system stability and power balancing control problems. The topic being interested in this research project is the impact of large scale wind power integration on power balancing control in the Danish power system. The Danish electricity system consists of two separate synchronous areas that are not connected to each other: the eastern part of Denmark which is synchronized to the Nordel system and the western part of Denmark which is synchronized to the UCTE system. With 75% of the Danish wind power capacity installed in the western part of Denmark; this is where the power system impacts are.

In this project, the generic models of an AGC system, conventional power plant, decentralized generating unit, and wind farm for long-term dynamic simulation are implemented and developed. A generic model with a similarity to the Danish power grid including the system interconnections with neighbouring countries is set up and the active power balance control is taken into account. An aggregated wind farm model with wind farm power control system is developed. An aggregated model of decentralized combined heat and power plant is implemented and it is analysed whether the power control should be changed with regard to taking part in the reserve. In an aggregated centralized thermal power plant model, secondary control and thermal dynamics of the boilers must be included. A model of the great belt link HVDC connection between the eastern part and the western part of the Danish systems and its regulating power control model is implemented. The utilization of the regulating power control incorporated in the eastern Denmark is expected to work together with that established in the western Denmark.

The total generic model has been used to evaluate the active power balance control and long-term system stability at different control strategies and at different loads and production situations. The power system analysis is carried out with regard to the power control from wind turbines in relation to the secondary control on the power plants and the regulating power control of the great belt link connection. Simulation studies with large scale wind power penetration in Denmark are presented. The operation and control of the Danish power system for the different control strategies should be analysed both at normal conditions and during very fluctuating power production from the wind farms.

Akarin Suwannarat
Aalborg, 2007

# Curriculum Vitae

Akarin Suwannarat was born on 4$^{th}$ June 1978 in Bangkok, Thailand. He attended Vajiravudh College in Bangkok from 1990 to 1996. After obtaining his secondary school certificate in sciences and mathematics in April 1996, he continued his study in Electrical Power Engineering at Thammasat University in June that same year. From April to May 1998, he did an internship at the National Control Centre (NCC), Electric Generating Authority of Thailand (EGAT) the largest Thailand's state owned utility. After obtaining Bachelor of Engineering in Electrical Power Engineering in March 2000, he continued his study in Energy Engineering at University of Applied Sciences Offenburg, Germany in October the same year.

From March to July 2001, Akarin Suwannarat did an internship at Freiburger Energie- und Wasserversorgung AG (FEW) in Freiburg, Germany under the framework of modelling and simulation of 20 kV system with DIgSILENT Power Factory program. He also worked as a research assistant in Solar Thermal 2000 project, which was supported by German Federal Ministry of Economic and Technology's research program during October 2001 to February 2002. From March to December 2002, he carried out his Master Thesis (Diplomarbeit) at the badenova AG & Co. KG. under supervision of Prof. Dr.-Ing. Elmar Bollin and Dipl.-Ing. Peter Heirch. The title of his master thesis is "Netzparallelbetrieb von Windkraftanlage am Mittelspannungsnetz der badenova AG & Co. KG " (Grid Integration of Wind Farms in the Distribution System). In February 2003, he obtained his M.Sc. in Energy Conversion and Management.

After graduation, Akarin Suwannarat worked as a project engineer with RWE Solutions AG. He was mainly responsible for project management, project installation, manage and coordinate activities of designated projects, and also communicate extensively with the clients as a representative of RWE Solutions AG in Thailand. From November 2004 till October 2007, he carried out the PhD project "Integration and Control of Wind Farm in the Danish Electricity System" (PSO 4102 project) under supervision of Associate Prof. Birgitte Bak-Jensen and Prof. Zhe Chen at the institute of energy technology, Aalborg University in Denmark. The project is made jointly between Institute of Energy technology; Aalborg University, DONG Energy A/S, Risø National Laboratory, Vattenfall A/S and Energinet.dk A/S and funded by PSO 2004 program.

Large scale wind power integration represents a new challenge to the Danish power system operation. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control and balancing problems.

Keeping the power balance between the western Denmark and the neighbouring systems is indicated here as the focus of this thesis. Power balancing control is developed to manage the imbalance taking into account the uncertain nature of wind power. The power system control strategies, which allows for active power balance might set up a limit of the wind power penetration.

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